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MULTI-MISSION OPTIMIZED RE-PLANNING IN AIR MOBILITY COMMAND'S CHANNEL ROUTE EXECUTION

by

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ABSTRACT

The United States Air Force's Air Mobility Command is responsible for creating a schedule and executing that schedule for a large-scale air mobility network that encompasses different mission areas. One of the mission areas is *channel route*. Channel route execution often experiences disruptions that motivate a need for changes in the current channel route schedule. Traditionally, re-planning the channel route schedule has been a manual process that usually stops after the first feasible set of changes is found, due to the challenges of large amounts of data and urgency for a re-plan. Other challenges include subjective trade-offs and a desire for minimal changes to the channel route schedule. We re-plan the channel route schedule using a set of integer programs and heuristics that overcomes these challenges. The integer programs' variables incorporate many of Air Mobility Command's operating constraints, so they do not have to be explicitly included in the formulations. The re-plan uses opportunities in the other mission areas and reroutes channel route aircraft. Finally, our methods can quickly find a solution, allow for "what-if" analysis and interaction with the user, and can be adapted to an evolution in Air Mobility Command's operations while the underlying models remain constant.

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1 Introduction

The United States military logistics system is an integral part in providing flexible and responsive transportation to project and sustain forces in times of war. Also important is the ability of the military logistics system to provide support for peacetime operations. The military logistics system must continuously adapt to a wide range of missions and geographical locations in a dynamic environment.

Ensuring smooth execution of the military logistics system is a challenging task. The military logistics system is a large, complex system that interfaces with many organizations. Furthermore, the current state of the world does not allow for the long lead time that existed during the Cold War for planning and scheduling of military logistics operations. To ensure high efficiency of the military logistics operations, interfacing organizations must be able to understand and analyze the effects that their decisions have on the system in a real-time environment.

The military logistics system operates on the framework of the *Defense Transportation System* (DTS). The United States Transportation Command (USTRANSCOM) operates over the DTS and is responsible for being "the single manager for defense transportation during peace and war" [31]. Through three *Transportation Component Commands* (TCCs) that report directly to USTRANSCOM and partnerships in the commercial sector, USTRANSCOM has the transportation resources necessary to perform its mission. The first TCC, the *Military Sealift Command* (MSC), has a mission to "provide reliable and efficient sealift, combat logistics forces, special mission ships and maritime services to meet customer requirements" [31]. The second TCC, the *Military Traffic Management Command* (MTMC), has a mission to "provide global surface transportation to meet National Security objectives in peace and war" [31]. The third TCC, the *Air Mobility Command* (AMC), has a mission to "provide airlift, air refueling, special air mission, and aeromedical evacuation for US forces" [31]. USTRANSCOM's partnerships in the commercial sector include the US airline industry, US maritime industry, and US domestic transportation industry. These partnerships provide USTRANSCOM with critical additional flexible transportation resources that are leveraged to operate in a dynamic global environment.

1.1 Research Scope: AMC's Execution of Channel Route Missions

AMC has the ability to move materiel and personnel long distances in a matter of hours. This movement occurs over the *AMC network*, which is the aircraft, aircrew, and aerial ports (i.e., airports) that support AMC missions. The AMC network is a complex system that includes 1000 *Department of Defense* (DoD) aircraft, 107,316 personnel, 16 permanent locations within the US, numerous aerial ports and international airports around the world, and partnerships with 25 commercial airlines [15], [17].

A key mission area of AMC are *channel route missions*. These missions provide airlift on a regular basis for non-deployment missions by transporting material and military personnel around the world. Channel route missions are not allocated dedicated aircraft but must share aircraft with other mission areas, such as exercises, deployment of forces in a contingency, and special assignment airlift missions (SAAMs). Channel route missions have a planning stage and execution stage. Channel route missions, scheduled during the planning stage, are not always executed as scheduled because other mission areas are less predictable and might have a higher priority for use of the aircraft that are scheduled to be used in channel route missions. To further complicate the execution of channel route missions, other problems caused by *disruptions* can affect the execution of channel route missions, such as unscheduled aircraft maintenance, weather, and unpredictable loading requirements for materiel and personnel.

The focus of this thesis is to develop methodologies that can help improve the execution of channel route missions. Because of the high operating costs of sustaining flight operations, small improvements in the execution of channel route missions can lead to significant efficiencies in aircraft usage and improvement in the ability of AMC to respond to changes in a dynamic environment. Recently, optimization-based network models have proved to be promising in improving the execution of flights in the commercial airline industry and the goal of this research is to explore the application of optimization-based models to the execution of channel route missions. Specifically, the models developed in this thesis are aimed at quickly finding solutions to problems caused by disruptions in the channel route schedule.

This research extends the work of Nielsen [24]. Nielsen developed an optimization-based model to automate the development of the initial cut of the *channel route schedule.* While the operational backgrounds of the planning and execution of channel route missions are very similar because both must adhere to AMC's operating rules, they do have different requirements. Mainly, solutions to problems caused by disruptions during execution must be found that minimize changes to the original schedule. The characteristics of the original schedule might impact the characteristics of the solutions to problems caused by disruptions, so Nielsen's work and this work are complementary.

Two key ideas motivate the research in this thesis. First, during the execution stage there is a large amount of information that must be processed. It is difficult to manually sift through this information to find solutions to problems caused by disruptions, let alone find optimal solutions. Currently, most of the implemented solutions to problems caused by disruptions are the first found because there is not enough time to consider alternatives. Second, there is an urgency to make decisions because it is costly to delay aircraft. As more time passes before a solution can be found, there is a real potential that opportunities are lost that would make the execution stage more efficient. An automated approach can quickly process the information and find a solution, allowing for good solutions and the ability to conduct "what-if" analysis.

1.2 Overview of Thesis

In this thesis we provide an overview of the current channel route planning and execution process and we present background information on previous network design formulations that we build upon to develop new formulations to help solve problems encountered in the execution of channel route misions. The remaining chapters are summarized as follows:

Chapter 2: *Air Mobility Command and the Current Channel Route Planning and Execution System*

This chapter describes specific elements of AMC that are relevant to the planning and execution of channel route missions. Furthermore, we present the challenges that AMC operators face on a daily basis to execute channel route missions, which we use to motivate the models and formulations presented in Chapter 4.

Chapter 3: *Background Information and Literature Review of Network Models*

The purpose of this chapter is to present ideas relating to network models that are extended to help solve the execution of channel route missions. Information is derived from traditional network models, concepts found in Nielsen [24], and network execution models found in the literature.

Chapter 4: *Functional Analysis and Modeling Approach*

In this chapter, we implement a closed loop model for the execution of channel route missions. The closed loop model is decomposed into separate steps that are either heuristics or network-based optimization formulations, including service network design and multi-airport ground holding formulations.

Chapter 5: *Results and Analysis*

This chapter presents results that are generated by using heuristics and models of Chapter 4 on several datasets with varying input parameter values. We also show the flexibility of the heuristics and models in solving disruptions during the execution of channel route missions.

Chapter 6: *Towards a Decision Support Tool*

In this chapter, we discuss how the concepts of this thesis can be tied together and extended to implement software that can provide decision support in an operational environment.

Chapter 7: *Summary and Future Research*

This chapter summarizes the work in the previous chapters and gives an overview of possible areas for future research.

2 Air Mobility Command and Current Channel Route Planning and Execution

Chapter 1 introduced the military logistics system with a focus on AMC. This chapter has three objectives. The first is to give a detailed account of the AMC organization and the physical components of *aircraft, aerial ports, and cargo*. The second is to explore the execution process of channel route missions. Finally, the third objective is to give the reader an understanding of the challenges faced by AMC.

2.1 Air Mobility Command

Air Mobility Command (AMC) is responsible for providing "airlift, air refueling, special air mission, and aeromedical evacuation for U.S. forces" [4]. The AMC mission provides the United States with a "global reach" capability during wartime [4]. In addition, the United States has come to rely on AMC in peacetime. AMC has responded to natural disasters, humanitarian needs, and peacekeeping missions around the world. Within AMC, the Tanker Airlift Control Center (TACC) "plans and directs tanker and transport aircraft operations around the world" on a daily basis [4], [24]. One of TACC's responsibilities continuing in both peacetime and wartime is channel route missions, the focus of this thesis.

2.1.1 AMC Customers

The Department of Defense (DoD) is composed of ten unified combatant commands, each led by a Commander in Chief (CINC). "A unified combatant command is composed of forces from two or more services (i.e., Air Force, Navy, Marine Corps., and Army), has a broad and continuing mission and is normally organized on a geographical basis" [16]. Six of the unified combatant commands are organized by geographical areas. The remaining four unified combatant commands are based on "worldwide functional responsibilities" [16]. The United States Transportation Command (USTRANSCOM) is one of the unified combatant commands that are based on functional responsibilities. USTRANSCOM's responsibility is to be the "single manager for defense transportation during peace and war" on the Defense Transportation System (DTS) [31]. The DTS is the "portion of the Nation's transportation infrastructure which supports DoD common-user transportation needs across the range of military operations. It consists of those common-user military and commercial assets, services, and systems organic to, contracted for, or controlled by DoD" [31].

In 1987, USTRANSCOM became responsible for peacetime missions in addition to its wartime missions. With the peacetime mission, the DTS began serving a wider variety of users. USTRANSCOM is responsible for the DTS as a "seller" of transportation services, while the users (e.g., CINCs and services) are the "customers" [32], [24]. The customers must be validated at a level equal to or above USTRANSCOM to be allowed use of the DTS. Customers include

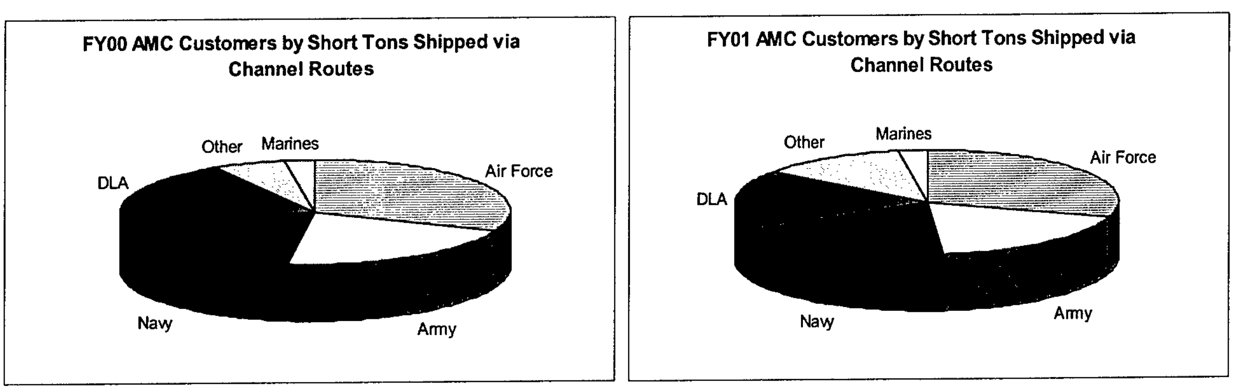


Figure 2-1: Percentage of cargo shipped by AMC customers in FY00 and FY01

all military services (i.e., Air Force, Army, Navy, and Marine Corps.), the CINCs of the six geographic unified combatant commands, the Defense Logistics Agency (DLA), the United Nations (UN), North Atlantic Treaty Organization (NATO), and other federal agencies such as the Central Intelligence Agency (CIA) [32], [24]. USTRANSCOM delegates all air transportation to AMC. The Air Force, Army and Navy make up the bulk of AMC's customers, followed by the DLA and Marines, as shown in *Figure 2-1* [32], [24].

2.1.2 AMC Mission Areas

AMC is responsible for six different mission areas. The six mission areas are training, Joint Airborne/Air Transportability Training (JA/ATTs), contingencies, exercises, special assignment airlift missions (SAAMs), and channel routes. *Figure 2-2* shows the relative priority and predictability of JA/ATTs, contingencies, SAAMs, and channel routes.

JA/ATTs, contingencies and exercise missions directly support war readiness and war fighting of the armed services, while SAAMs and channel routes missions are used to support many organizations in both peacetime and wartime. Because AMC uses the same aircraft for all mission areas, individual missions within a mission area are assigned a Joint Chiefs of Staff (JCS) priority code. Lower priority mission areas can lose airlift support to higher priority

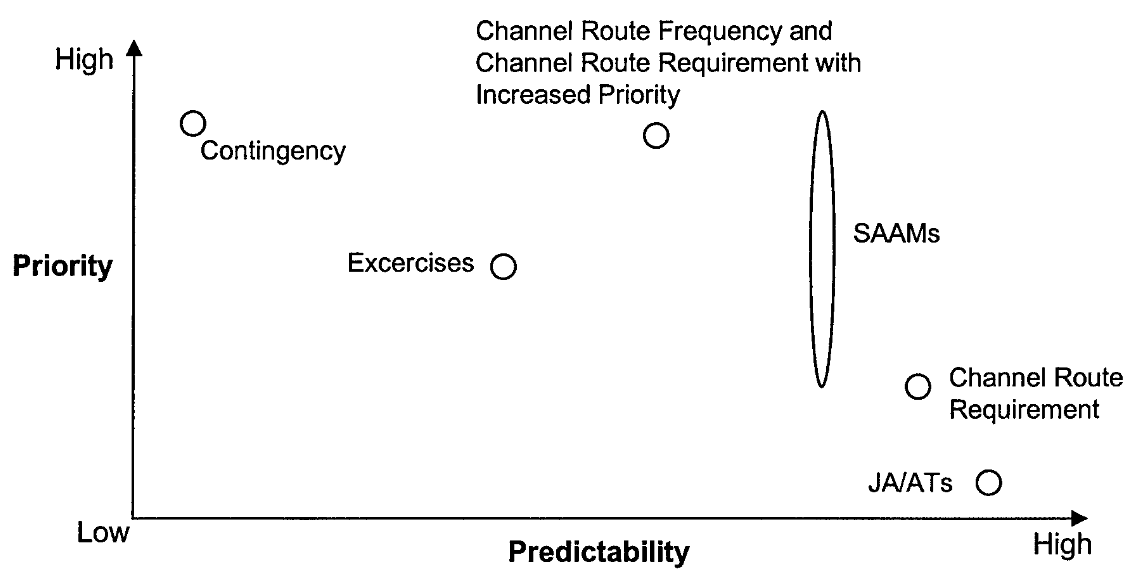


Figure 2-2: Mission areas priority vs. predictability chart, notionally based upon Table 2-3

mission areas and might lose aircraft to other mission areas at the last moment with little predictability. During a mission's planning period, the mission areas that have a high level of predictability and a high JCS priority code can be confidently assigned aircraft, because the missions will have little chance of not being supported. However, mission areas that have a high priority and small level of predictability, or a low priority and high level of predictability are difficult to plan [24]. The final plan of each mission area is not certain until missions are executed and aircraft are in the air.

2.1.2.1 Training

These missions are planned at the Air Force's operational units to enhance specific skills of the pilots and aircraft crew members. The operational units will coordinate their plans with AMC to ensure that there are enough pilots to fly other mission areas. Usually, the operational units have aircraft set aside for training missions, which are called "trainers." The remaining aircraft of an operational unit is contracted by AMC for the remaining mission areas.

2.1.2.2 JA/ATTs

JA/ATT operations are used for tactical operations training. These tactical operations include airland and airdrop missions, where Air Force, Marine and Navy personnel are inserted into the "battlefield" [4]. For example, an Air Force aircraft is used to airdrop para rescue special forces. JA/ATTs require prior planning, so they are predictable. The individual units plan JA/ATTs, while AMC allocates aircraft to the units.

2.1.2.3 Contingencies

Contingencies are real world applications of force. For example, the initial operations in Iraq and Afghanistan are contingencies. Contingency missions are used to deploy forces in a contingency. The Air Force has a vision of being an "expeditionary force" and contingency missions are at the core of this vision. Thus, contingency missions have a short planning period and high priority, so they can cause drastic disturbances to the execution of other mission areas. The contingency missions are focused on the deployment rather than support of forces.

2.1.2.4 Exercises

Exercises simulate contingencies and are used to ensure military readiness for contingencies. However, exercises have a longer timeline for planning and are a lower priority than contingency missions. Exercises give the Air Force units a chance to practice force deployment. They are different from training missions because of their larger training scope. Exercises include practicing deploying forces with other Air Force units and units from other services. The military takes enormous effort in ensuring that exercises replicate contingencies to the most practical extent.

2.1.2.5 SAAMs

SAAMs are used by AMC's customers to buy space on an AMC aircraft or pay for an entire aircraft for a customer determined point to point route with unique requirements, such as the number of passengers involved, the weight or size of cargo, the urgency or sensitivity of movement, or other special factors. Examples of SAAMs include Presidential convoy support and shipment of classified cargo between Army posts.

2.1.2.6 Channel Routes

Channel route missions are used to carry cargo for AMC's customers. USTRANSCOM validates (see §2.1.4.5) the customers request for cargo shipment. Unlike the other mission areas, most information regarding channel routes is handled as unclassified material.

For the remainder of this thesis, we will use the following terminology, some of which can be found in Nielsen [24]. The *AMC network* refers to AMC's aircraft, cargo, and bases used by all mission areas. A *channel route mission* refers to the route on which a piece of *channel cargo* will travel by aircraft from its origin to its destination. A *channel route schedule* of *channel route missions* will be executed in *channel route execution*. In later chapters, we build models to assist decision makers in finding solutions to disruptions in the *channel route schedule* that occur in *channel route execution* when the schedule interacts with other mission areas.

Channel route missions fall into one of two categories, *frequency* and *requirements*. Frequency channel routes are regularly scheduled flights that are used for locations that do not have enough cargo to fill an entire aircraft, but provide "operational necessity and quality of life requirements in remote areas" [31]. Frequency channel routes have a high predictability and high priority. Requirements channel routes are used to provide transportation for scheduled cargo and alleviate large cargo backlogs at the aerial ports. Requirements channel route missions have a high predictability and a low priority. They might have a contingency designation in a wartime scenario to increase the priority of channel route missions sustaining contingency forces, so the missions can adequately compete against contingency missions for limited aircraft resources.

2.1.3 The Tanker Airlift Control Center

On 1 June 1992, "the Military Airlift Command (MAC) and the Strategic Air Command (SAC) were inactivated and the Air Mobility Command (AMC) formed from elements of these two historic organizations" [4]. MAC was responsible for the Air Force's large cargo aircraft, while SAC was responsible for the air-refueling aircraft used to support its strategic bomber force [15]. After the collapse of the Soviet Union, the DoD formed AMC to be responsible for both the cargo and air-refueling aircraft.

Before AMC operations began, command and control responsibilities for the cargo and air-refueling aircraft were decentralized throughout the Air Force. The Tanker Airlift Control Center (TACC), located at Scott AFB, Illinois within AMC and neighboring USTRANSCOM, was created on 1 April 1992 to centralize the command and control process. The TACC tasks, schedules, executes and recovers "airlift, air-refueling, aeromedical, and operational support missions" [4], [24].

The TACC is composed of nine directorates (see *Figure 2-3*), which are based on the AMC's mission areas. Four of the directorates are directly involved in the planning and re-planning of missions. The *Mobility Management Directorate,* also referred to as the *barrel,* is responsible for allocating aircraft and aircrews among the different mission areas. The barrel might make changes to its allocations as the mission areas change their schedules. The *Command and Control Directorate*, referred to as the *floor*, is responsible for executing and monitoring missions on a minute-by-minute basis and does not schedule any missions. The *Global Channels Directorate* is responsible for scheduling channel route missions and will also be on call to help the floor replan missions during execution. The *Global Readiness Directorate* oversees both the exercises and contingencies mission areas. The *Current Operations Directorate* plans missions that do not fit into the other mission areas.

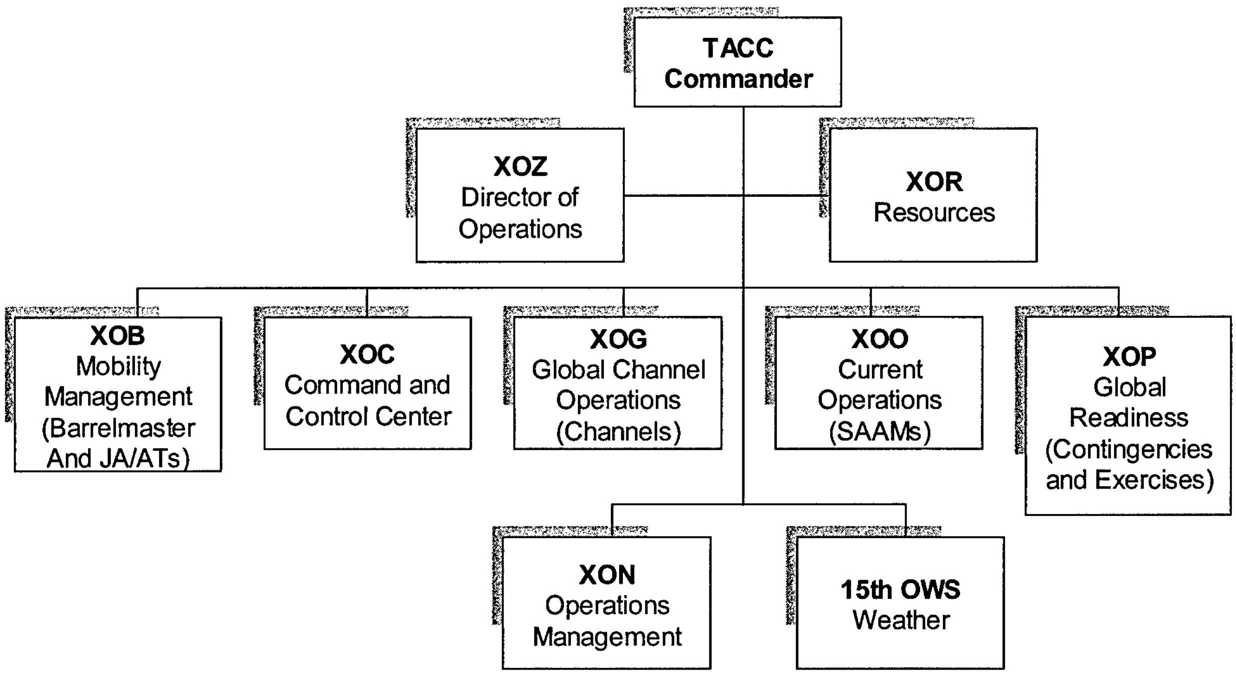


Figure 2-3: TACC organizational chart

External to the TACC, AMC must create an ad hoc command and control structure when operating in areas that have a limited or nonexistent AMC presence. AMC has the ability to quickly set up a control structure at these locations using a Tanker Airlift Control Element (TALCE). Examples of situations requiring a TALCE are Presidential convoys to remote locations or a build up for a contingency. A TALCE is a composite group that has all the elements needed to begin moving cargo and passengers into a location, including maintenance teams, security forces, communication personnel, and cargo and passenger handling teams [4].

2.1.4 AMC's Physical System

This section describes the physical system of AMC. AMC has permanent operations at sixteen bases in the US, employs 107,316 people, and is responsible for nearly 1000 DoD aircraft [15]. At an abstract level, the system consists of *aerial ports*, *aircraft*, *aircrew*, *cargo*, *cargo flow* and *troop movements*.

2.1.4.1 Aerial Ports

Aerial ports are military locations that have the infrastructure to process cargo and support DoD and commercial aircraft contracted to support AMC. Aerial ports contain runways, parking and servicing ramps for aircraft, maintenance hangars, fuel storage, and cargo processing equipment and facilities. Some aerial ports are the home base locations for one or more DoD aircraft types. Each aerial port is designated a unique international civil aviation organization (ICAO) code that is useful in identifying the aerial port.

The amount of infrastructure at an aerial port limits the maximum number of aircraft that can be at the aerial port. This limit is known as the maximum on ground (MOG). The number of aircraft that can be parked at an aerial port is constrained by the parking MOG (PMOG). Aircraft are also limited by the capacity of the fueling equipment, called the fueling MOG (FMOG). There are other resource constraints at an aerial port that make up the working MOG (WMOG) such as material handling, maintenance and security.

Aircraft movement into and out of aerial ports can be restricted by associated operating hours, Bird Air Strike Hours (BASH) and in some cases, quiet hours. Operating hours are when personnel are on duty at an aerial port. BASH hours restrict aircraft landing and takeoff during certain times of wildlife migration to ensure safety. Some aerial ports, especially those located near large population centers, might place restrictions on the types of aircraft that can take off and land during certain times of the day [24].

2.1.4.2 Aircraft

This section describes organic (DoD owned) and commercial aircraft that fly AMC's missions, including channel route missions. Commercial aircraft resources are derived from commercial airlines that participate in the Civil Reserve Air Fleet (CRAF).

2.1.4.2.1 Organic

Organic aircraft are DoD owned aircraft. Cargo and passengers are transported on the Boeing C-17 Globemaster III, Lockheed Martin C-141 Starlifter, Lockheed Martin C-130 Hercules, Lockheed Martin C-5 Galaxy, Boeing KC-10 Extender, and Boeing KC-135 Stratotanker. AMC also uses the Gates C-21 Learjet and Raytheon-Beech C-12 Huron for passenger transportation. The first letter in the Air Force's alphanumeric identifier represents the

Aircraft Type	Max Cargo (lbs)	Max Pallets (463L)	Max Passengers	Range (miles)
C-141	68725	13	150	2500
C-5	291000	36	73	3500
KC-10	169350	25	65	2600
KC-135	30000	6	54	2500
C-17	172200	18	102	2800
C-130	44400	6	91	3500
C-9	9000	—	36	2000
C-21	3153	—	6	2300
C-12	4200	—	8	1900

Table 2-1: Organic aircraft operating constraints

primary mission that the aircraft performs and the second letter represents the secondary mission. For instance, C represents transport/cargo and K represents air refueling/tanker. While the KC-10 and KC-135 primarily provide in-air refueling of military aircraft, they can be configured to carry cargo. *Table 2-1* lists some of the operating constraints of organic aircraft used by AMC.

Organic aircraft and associated personnel are organized by Air Force wings. Within the wings are squadrons that have a single type of aircraft. A squadron is permanently stationed at an aerial port that it may share with other squadrons. The squadrons are responsible for the maintenance of the aircraft and training of the aircrews. Furthermore, squadrons have contract and trainer aircraft. The Air Force wings will report to AMC thirty days prior to the execution month with the number of aircraft and associated aircrew that will be available for contract (see §2.1.4.3), setting the maximum number of resources that AMC can use from the squadrons. The remaining aircraft in the squadron are the squadron's trainers, which are used for local training missions [24].

2.1.4.2.2 Commercial Augmentation

Situations arise during peacetime and wartime for which there is not enough organic aircraft capacity for AMC to transport all of its customers' cargo. To augment wartime mobilization, AMC relies on the Commercial Civil Reserve Air Fleet (CRAF) program. CRAF was initiated in 1951 to mobilize for Cold War operations [17]. Commercial carriers that commit aircraft to CRAF are allowed to bid for peacetime *fixed-buy contracts* and *expansion-buy contracts* that are worth nearly two billion dollars a year.

CIVIL RESERVE AIR FLEET (CRAF)

CRAF has made an impact since the Cold War in operations Iraqi Freedom and Enduring Freedom, and the Persian Gulf War. During the Persian Gulf War, "two-thirds of the troops and one-quarter of the air cargo" was transported by commercial airlines. In addition to the aircraft, CRAF gives AMC access to "crews, en route infrastructure, fuel, maintenance, and ground support" [17]. The aircraft committed to CRAF are activated in three stages—Committed Expansion, Defense Airlift Emergency, and National Emergency—with each successive stage being less likely to be activated in a time of war. While the participating airlines do not get paid for committing their aircraft to CRAF, they do get reimbursed if the CRAF is activated. Because of the risk and uncertainty imposed on airlines that participate in CRAF, participants are given the chance to bid on peacetime *fixed-buy contracts* and *expansion-buy contracts* in proportion to the participants' CRAF commitment. In addition, those airlines that commit to a lower activation stage (and are more likely to be activated) will be rewarded with a higher proportion of fixed-buy contracts and expansion-buy contracts. *Table 2-2* shows the participating airlines and the number of aircraft dedicated to CRAF for 2003 [17].

FIXED-BUY CONTRACTS

Fixed-Buy contracts average seventy-five million dollars a year between FY97 through FY01 [17]. AMC must decide how many fixed-buy contracts it will purchase for the entire fiscal year. This is a challenge for AMC because it must balance customer service, the interests of CRAF participants, and its own need of ensuring AMC aircrew receive enough flying hours for training (see §2.1.4.3). AMC decides on the number of fixed-buy contracts and the corresponding flight routes that it will need by using historical fixed-buy contract data, the number of flying hours needed for training AMC aircrews and historical cargo data. Then AMC negotiates with the commercial airlines to decide the *fixed-buy rate* and the commercial airlines bid on the contracts at the fixed-buy rate. Nielsen's optimization models may be used to analyze fixed-buy contract routes (see [24], §2.2.3.2).

CRAF Cargo Aircraft		
Airline	***Number of WBE Committed***	***Pct of Airline's Long-Range Fleet***
Airborne Express	3	25
Atlantis Air	32	100
Federal Express	111	100
Gemini Air Cargo	16	100
Northwest	12	100
Omni Air Intl.	2	100
Polar Air Cargo	16	100
DHL Corp.	7	100
Evergreen	10	100
Southern Air	4	100
UPS	11	25
World	5	100
Air Transport Intl.	13	100
Arrow Air	10	100
CRAF Passenger & Aero-medical Aircraft		
American Trans Air	37	100
Northwest	55	93
Omni Air Intnl.	5	100
American	100	65
Continental	80	90
Delta	72	49
North American	3	100
United	96	60
USAirways	20	100
World	7	100
Hawaiin	4	33

Table 2-2: CRAF participants

Fixed-buy contracts are important to channel route mission planners and operators because the routes flown under the contracts will not be canceled due to higher priority missions (see §2.1.2). Also, the contracts guarantee a high level of reliability from the commercial airlines, because the airlines are required by contract to provide the crews and maintenance for the aircraft. From a channel route perspective, commercial and organic aircraft types each have advantages. Organic are less expensive and have more flexibility on flight routes, while commercial aircraft have a higher level of dependability and reliability.

During the execution of channel route missions, AMC might want to change the routing or schedule of a fixed-buy aircraft. Whether or not a change is made depends on the needs of the commercial airlines. For instance, airlines might have follow-on missions with other non-AMC contracts or they might not have enough crew to perform the change. Commercial airlines are not required by contract to honor AMC's requests for changes, however, AMC and CRAF members may negotiate to find mutually beneficial solutions.

EXPANSION-BUY CONTRACTS

Expansion-buy contracts meet short-notice requirements and are more volatile than fixed-buy contracts, reflecting the dynamic nature of executing AMC missions. The average annual expansion-buy cost was ninety-seven million dollars between FY97 through FY01. AMC negotiates with airlines for an *expansion-buy rate*, which is higher than the fixed-buy rate. Expansion-buy contracts are useful for channel route missions when aircraft are lost to higher priority missions, cargo is underestimated at an aerial port, or other reasons. The length of expansion-buy contracts can vary in time from a single mission to an entire fiscal year.

Expansion-buy contracts are also more flexible than fixed-buy contracts because the commercial airline has less time to develop its own schedule around the contract, enabling AMC to make more last minute changes to expansion-buy contracts than to fixed-buy contracts. *Figure 2-4* compares the cost per year of fixed-buy contracts and expansion-buy contracts from FY90-FY02 [17].

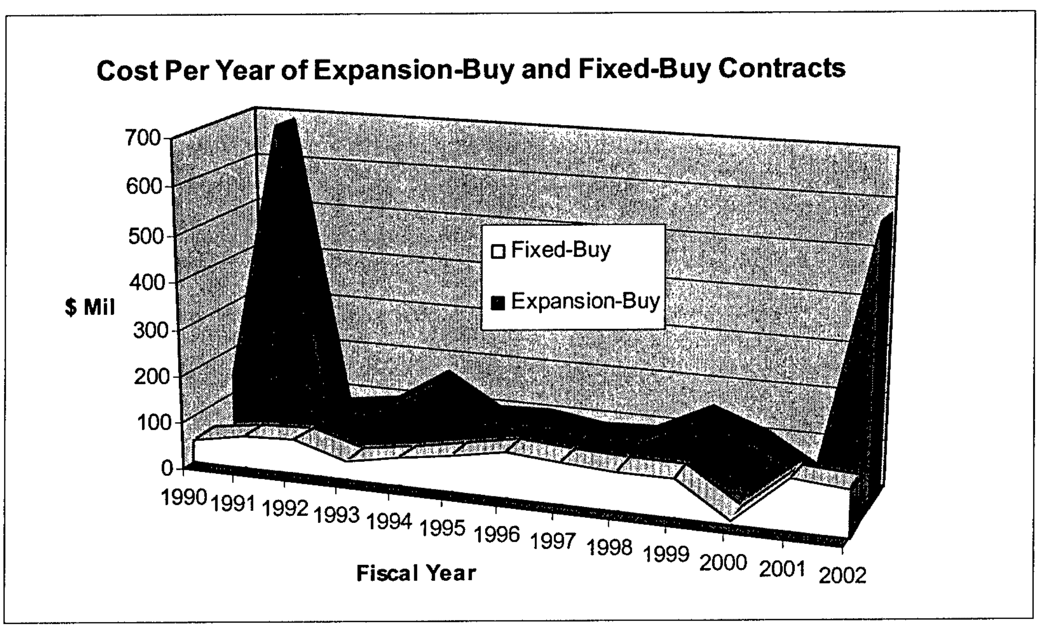


Figure 2-4: Comparison of volatility of expansion-buy and fixed-buy contracts

2.1.4.3 Aircrew

Aircrews, like organic aircraft, are contracted by AMC from individual Air Force squadrons. For safety, aircrews must adhere to the crew duty day (CDD) limit, which specifies the maximum number of hours a crew can fly followed by the minimum number of hours of uninterrupted crew rest. When executing channel route missions, AMC sometimes uses two strategies to adhere to the CDD guidelines while ensuring timely transportation of cargo. The first is to augment crews, where more than one crew is assigned to an aircraft so they can alternate between rest and flying. The second is to preposition aircrew at select locations so a fresh aircrew can finish a long mission [24].

To ensure the readiness of aircrew and even dispersion of experience among pilots, AMC implements the Flying Hour Program (FHP), which is approved by the US Congress. The FHP specifies the number of hours that each aircraft type must fly each year which, in turn, will give aircrew experience.

2.1.4.4 Cargo

There are five different classifications of cargo that are moved by channel route missions—bulk, oversize, outsize, rolling stock and special. Bulk cargo is cargo that can be placed on a standardized 463L pallet. The 463L pallet measures 108 inches in length, 88 inches in width, and can be loaded a maximum of 96 inches tall. The 463L pallet can be loaded in different configurations to fit the interior shape of aircraft (see *Figure 2-5*). Bulk cargo can be transported on the C-5, C-17, C-141, C-130 and KC-10 aircraft. Oversize cargo exceeds the usable limit of the 463L pallet but is less than 1,090 inches in length, 117 inches in width, and 105 inches in height. Sometimes oversize cargo can be placed on multiple 463L pallets. Outsize cargo exceeds the dimensions of the maximum oversize cargo and can only be transported on the C-5 and C-17 aircraft. Examples of outsize cargo are tanks and helicopters. Rolling stock cargo represents equipment that can be driven or rolled directly onto an aircraft, such as HUMVEE vehicles. Special cargo, such as space satellites or nuclear weapons, requires specialized preparation and handling procedures.

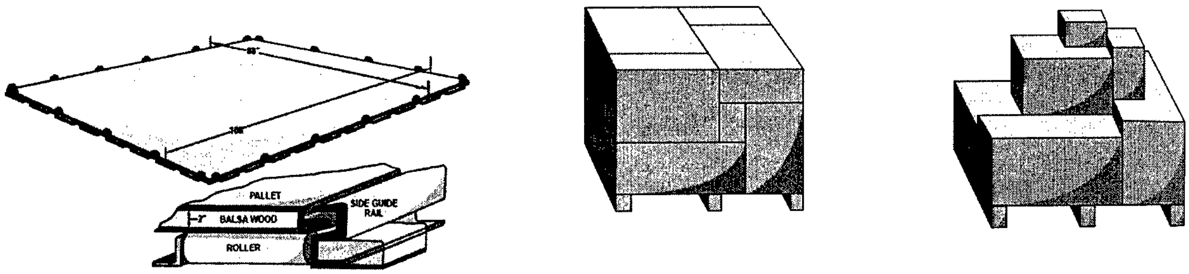


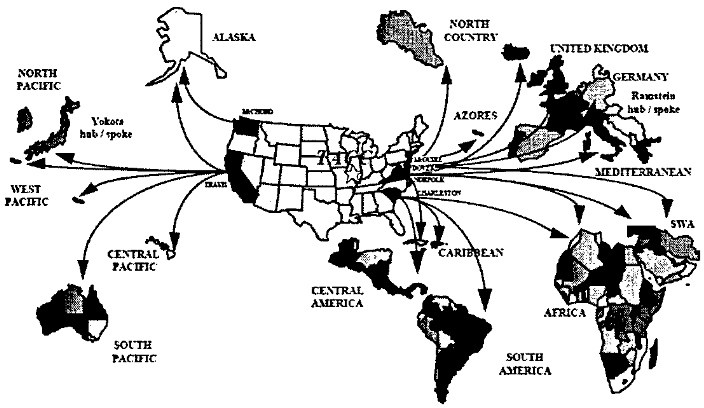
Figure 2-5: Standard pallet and possible loading configurations

USTRANSCOM prioritizes customer cargo, in order from highest to lowest, as 999 ("triple 9"), TP-1, TP-2, TP-3, and TP-4. The priority system helps determine the mode of transportation. The most urgent cargo is in the 999 category, which will always be transported by aircraft, while TP-3 may be sent by air and TP-4 cargo will almost always be sent by ground transportation. The performance of channel route missions transporting TP-1 priority cargo is measured by the time definite delivery (TDD) metric to guarantee a quick transit time for AMC's customers.

Some cargo is classified as hazardous material (HAZMAT), such as radioactive material, explosives, corrosives, and gasoline. Items, such as hairspray and batteries, are considered hazardous when transported in bulk. Transportation of HAZMAT is regulated by the DoD and United Nations (UN). For example, the number of passengers and the different types of cargo that can be transported together might be limited when transported with hazardous cargo. Hazardous cargo requires special preparation and documentation at aerial ports [3].

2.1.4.5 Cargo Flow

An aerial port where cargo originates is defined as an aerial port of embarkation (APOE). The destination aerial port of the cargo is defined as the aerial port of debarkation (APOD). There are six main APOEs within the CONUS, with two on the west coast (e.g., McCord and Travis) and four on the east coast (e.g., Norfolk and Dover). The majority of channel route cargo leaving the CONUS is processed at one of the six APOEs and each APOE generally serves certain regions of the world. Major APOEs OCONUS are called hubs, which are located at Yokota AB, Japan and Ramstein AB, Germany. See *Figure 2-6* for the locations of the two OCONUS hubs and the six main CONUS APOEs with their respective areas of service [14].



APOE	Regions Served
McCord (West)	Alaska
Travis (West)	Hawaii, Japan, Australia
McGuire (East)	North Country, Azores, Europe
Charleston (East)	Central and South America, Africa, Caribbean
Norfolk (East)	Caribbean, Africa, Middle East
Dover (East)	Africa, Middle East, Europe

Figure 2-6: APOEs and the respective areas of service

Cargo can travel from an APOE to an APOD and then be unloaded from the first aircraft and loaded onto a second aircraft. The APOD then becomes an APOE and the cargo is flown to another APOD. This occurs in *hub and spoke systems* and *transloading*. The hub and spoke systems are used at the two major hubs and contingency theaters of operations. They function much like commercial airlines' hub and spoke systems. Once aircraft arrive to a hub, its cargo will be unloaded, sorted, and loaded onto different aircraft. Hub and spoke systems are used in contingency theatres of operations because an aircraft that is excellent for long range transportation, such as the C-5, might not do well in the theater of operations. Transloading can occur at any aerial port that has cargo handling equipment and often occurs to fix disruptions in the channel route schedule. One example is the *tail swap* where one aircraft will take over another's channel route mission, and cargo is transloaded between aircraft. *Figure 2-7* presents examples of material handling equipment [25].

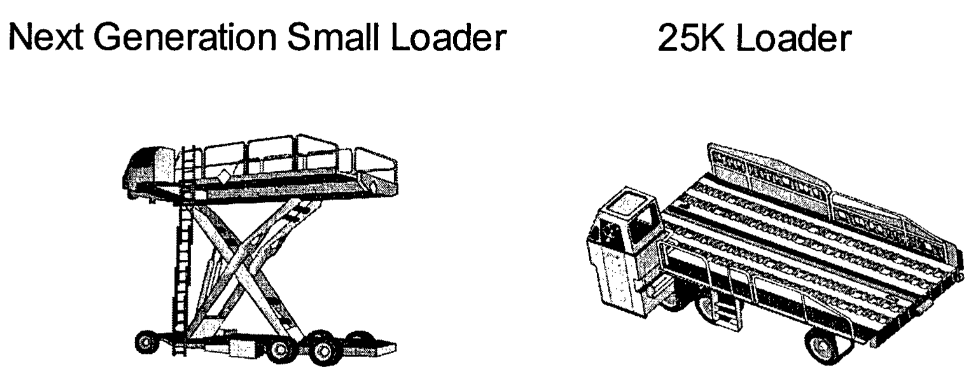


Figure 2-7: Examples of material handling equipment

Ninety-nine percent of the cargo transported by AMC is considered to be bulk cargo, that can be placed on any aircraft using the standard 463L pallet. However, other factors must also be taken into consideration such as weight and balance of pallets, HAZMAT (see §2.1.4.4), and diplomatic clearances (DIPS). To enter the airspace of foreign countries that do not have a blanket clearance for US aircraft, DIPS are required. To obtain DIPS, aircraft must meet lead-time, operational, route, cargo and other requirements that will vary from country to country. Lead-time, usually around two weeks, refers to the advance notice that some countries require of a DIPS request. Short-notice requests must be justified and might not be approved. Operational requirements include the type of aircraft and the window of time for entry into and exit out of the country. Route considerations include whether the flight will be landing at a specific aerial port or simply flying over the country and the geographical entry and exit points. Cargo requirements usually limit the types of HAZMAT material that can be flown into a country but could include other items. DIPS add a level of complexity to AMC's operations due to their relative inflexibility and numerous unique restrictions.

The routes of channel route missions must be validated by USTRANSCOM. This process is initiated by a customer requesting transportation for cargo. Included in the request is the amount of cargo, the origin and destination of the cargo and/or the frequency of service desired (i.e. frequency channel route missions). Next, USTRANSCOM will validate the request by assigning the cargo a priority (see §2.1.4.4) and decide on the type of transportation that will be used. If the cargo will be transported by air, then USTRANSCOM will determine the allowable routings for the channel route missions that will transport the cargo. The allowable routings will be published by AMC via the *sequence listing*. The sequence listing includes all validated channel route missions by giving the approved rate of cargo flow between specific aerial ports and serves as an APOE to APOD routing guide. The routing of aircraft in the channel route schedule must adhere to the sequence listing, and a single channel route mission may travel along multiple routes that are in the sequence listing as channel route missions are not merely direct origin to destination flights. However, during channel route execution it is possible that rerouted aircraft fly a route that is not on the sequence listing, but the mission must start and end at the same APOE and APOD, respectively. Aircraft that fly routes with cargo being measured by TDD are almost never altered.

2.1.4.6 Troop Movements

Troop movements include aerial evacuation (AE) missions and personnel repositioning. AE missions are the planned and unplanned movement of injured and ill military personnel throughout the world and the transportation of human remains (HR). At AMC, the AE mission area is the responsibility of the same organization that plans and executes channel route missions. Within CONUS, AE mission schedulers use frequency channel route missions to transport patients between hospitals with different specialties, while AE mission schedulers will create an AE network system in OCONUS using CRAF aircraft. However, unexpected heavy demand for AE missions are satisfied by organic aircraft, so organic aircraft assigned to channel route missions might be reassigned to fly unplanned AE missions. Almost all organic aircraft have the ability to fly AE missions if appropriately trained medical personnel are available to fly with the mission. Organic aircraft flying exclusive AE missions are allowed to bear the Red Cross symbol. Personnel repositioning is the transportation of personnel and their individual gear and, as with the transportation of cargo, have an APOE and APOD. CRAF commercial passenger airlines are commonly used for personnel repositioning.

2.2 Planning & Execution of Channel Route Missions

Planning and execution of channel route missions occurs over a three month period. The first two months is a *planning period* and the third month is an *execution month.* During the planning period, the *organic scheduler* creates an *initial cut* of the channel route schedule. The *CONUS cargo bookie* and *barrelmaster* will review the initial cut and give feedback to the organic scheduler who makes appropriate changes before it is published on the *Global Decision Support System.* Once published, other organizations make inputs by coordinating with the organic scheduler to make incremental changes to the channel route schedule. Finally, the missions are executed during the execution month, with individual missions entering the *execution phase* twenty-four hours before the mission begins and remaining in the execution phase until the mission ends. The execution month uses the schedule created in the planning period, but requires reactionary solutions to problems that arise in missions in the execution phase. *Figure 2-8* shows the overlapping nature of planning periods and execution months.

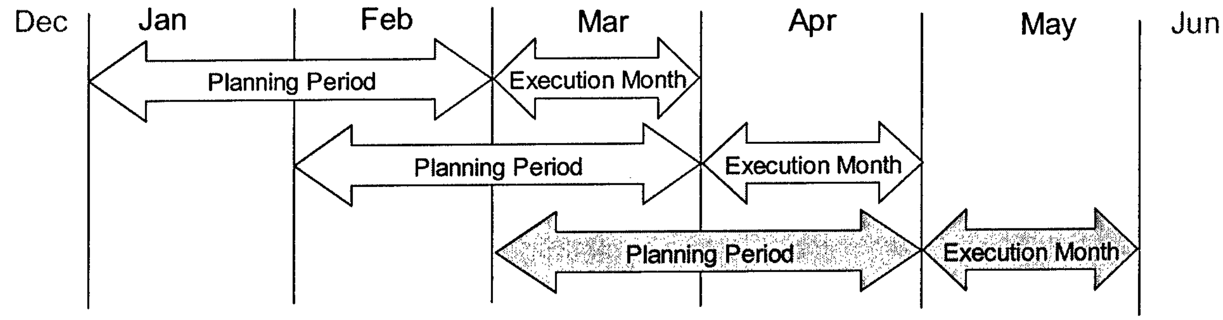


Figure 2-8: The channel route planning period and execution month

During the execution month, the CONUS cargo bookie, barrelmaster, and organic scheduler still make updates to the schedule and a variety of organizations still have inputs. In addition, the CONUS cargo bookie finds solutions to disturbances in the plan that occur when excess cargo arrives at CONUS APOEs, while the *offshore cargo bookie*, who is not involved during the planning period, finds solutions to excess cargo that arrives at OCONUS APOEs. Once missions enter the execution phase, *the floor* becomes responsible for the channel route missions, but often seeks advice from the organic schedulers and barrelmasters. The CONUS and offshore cargo bookies continue to coordinate with the floor to find solutions to cargo flow problems that might be implemented beyond the execution phase. This section summarizes AMC's channel route scheduling and execution process, and describes disturbances that often occur in the channel route schedule. *Figure 2-9* shows the timeline for the planning of a channel route schedule, from when it is first initiated until the end of the execution month.

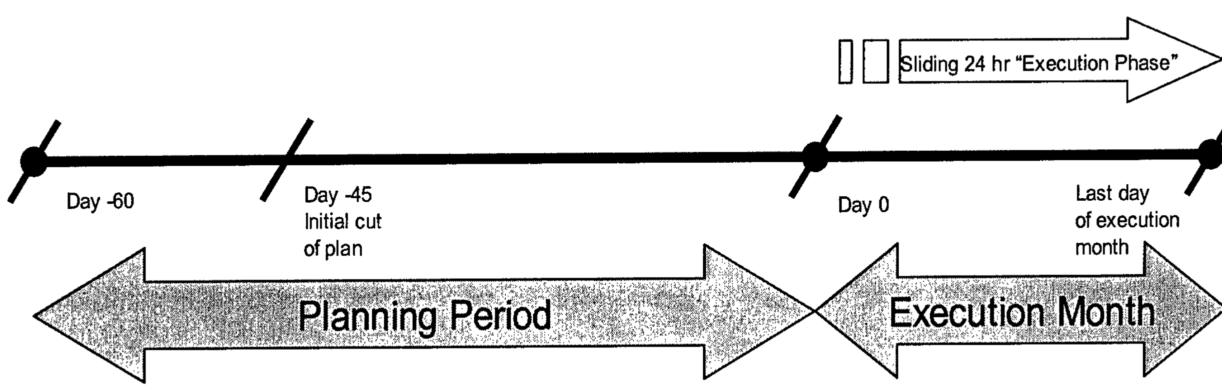


Figure 2-9: The channel route planning and execution timeline of events

2.2.1 Planning and Execution Objectives

AMC has three high level objectives for channel route missions—Readiness, Customer Service and Net Operating Result (NOR) [24]. The ability to perform as expected in a wartime situation is considered the readiness of a military unit. Readiness is achieved through peacetime training and practice of job skills. The exercises mission area helps military units learn to work together and AMC uses the FHP (see §2.1.4.3) to achieve currency and proficiency of its pilots' skills. Customer service is AMC's mission of supporting its customers' ability to perform their own mission. AMC does not intend to make a profit. Rather it ensures that its operating costs equal the funding for its flying hours combined with reimbursement for transporting cargo for its customers. This objective is the NOR. Schedulers plan channel route missions in a timeframe that could allow them to focus on AMC's high level objectives [24], but as the time frame shifts from days in the planning stage to minutes in the execution phase, focus shifts from meeting high level objectives to reactionary decision making and an urgency to meet the short term mission goals.

During the execution month and especially during the execution phase of channel route missions, AMC's high level objectives transition to reactionary decision making and a focus on completing individual missions. This type of shift is inherent in the differences between planning and execution. If plans proceeded as scheduled, then there would be no need for operators to alter plans as they were executed. However, disturbances often occur that upset the timing or routing of channel route missions. Therefore, decisions made in execution are reactionary because they fix what has gone wrong.

2.2.2 Joint Chiefs of Staff Priority System

Because AMC has limited aircraft resources, it needs a system to help allocate its aircraft resources to AMC airlift missions. For peacetime missions, AMC uses the JCS airlift priority system to assign JCS airlift priority codes to AMC airlift missions (see §2.1.2). Customers submit a JCS priority code for their cargo when requesting transportation from USTRANSCOM. During a contingency, a percentage of the airlift resources will be removed from the JCS airlift priority system and given to commanders that are responsible for the war effort. *Table 2-3* on the next page presents an overview of the JCS airlift priority system using alphanumeric codes.

JCS Priorities (From High to Low)	Description
1A1-1A4	Presidential and JCS directed missions. SAAMs will often fall in this category.
1B1-1B3	Secretary of Defense directed missions and **frequency channels**. **Contingency frequency and contingency requirement channels**.
2A1-2A2	Missions that support the state of military readiness for immediate combat.
2B1-2B2	Missions that support military exercises.
3A1-3A3	Missions that support the combat readiness of the military and **requirements channels**.
3B1-3B4	In support of JA/ATT missions.
4A1-4A2	Missions that support activities for employment in support of war plans.
4B1-4B3	Missions that support non DoD activities or aircraft that are used as static displays in public and military events.

Table 2-3: Joint Chiefs of Staff priority system

2.2.3 Channel Route Planning and Execution Tools

The Global Decision Support System (GDSS) is AMC's overarching database that supports the TACC's command and control of aircraft. GDSS stores information such as the routes, departure and arrival times of specific aircraft, the priority of missions, and the status of DIPS and HAZMAT. Aircraft squadrons access the information on GDSS to show the missions they are assigned to fly. The data in GDSS can be accessed and updated using different user interface software such as the Integrated Management Tool (IMT), Consolidated Air Mobility Planning System (CAMPS), and Global Air Transportation Execution System (GATES). The IMT consolidates the command and control data of GDSS with weather and logistical information to support flight managers during the execution of flight missions. CAMPS is an interface used by organic schedulers to assign aircraft resources to missions and is used during the execution month to make updates to the channel route schedule. GATES tracks AMC's cargo and passenger information at aerial ports and is used as a resource manager to ensure AMC's customer's cargo is being transported.

Besides the GDSS database and the user interface software, TACC personnel rely on a manual process during the execution of missions. AMC's decision making and problem solving policies are outlined by Air Force Instructions (AFI). From the policies in the AFIs, AMC has created a series of forms that present procedures adhering to the policies in a step-by-step format that cover specific types of disruptions in the schedule. After each step is followed, it is checked off to help ensure compliance. The checklist forms help guide personnel on the floor to either resolve disruptions or to inform a supervisor of disruptions. A disruption that cannot be easily resolved using the software tools and checklists requires innovation, experience, job training, and intuition.

2.2.4 The Planning Period

The organic schedulers are responsible for scheduling all channel route missions during the planning period that begins sixty days before the execution month. The organic scheduler initiates the planning period by beginning development on the initial cut. Currently, the organic scheduler creates the initial cut of the channel route schedule without the aid of a decision support tool by modifying the previous month's schedule to account for "known special circumstances" [24]. Once the initial cut has been created, it is sent to the barrelmaster and CONUS cargo bookie. The barrelmaster is responsible for allocating aircraft among all the mission areas and will determine how many aircraft the organic scheduler receives in support of the channel route schedule. The CONUS cargo bookie ensures that the initial cut of the channel route schedule is capable of transporting all validated cargo. If the amount of organic aircraft capacity does not meet the needs of the channel route schedule, then the organic scheduler coordinates with the *commercial scheduler* to use fixed-buy commercial aircraft. The organic scheduler updates the initial cut using the feedback from the barrelmaster and CONUS cargo bookie and post the resulting channel route schedule on GDSS. Once the schedule is posted on GDSS, it becomes visible to other TACC organizations and Air Force wings, which coordinate with the organic scheduler to make incremental changes to the channel route schedule. *Figure 2-10* on the next page shows the current process used to create the channel route schedule [24].

Nielsen developed a proof-of-concept decision support tool to help the organic scheduler create the initial cut of the channel route schedule during the planning period. The tool simultaneously considers all inputs to help create the initial cut [24]. The reader is directed to Nielsen's work for a more detailed explanation of the planning period and the concepts of this decision support tool.

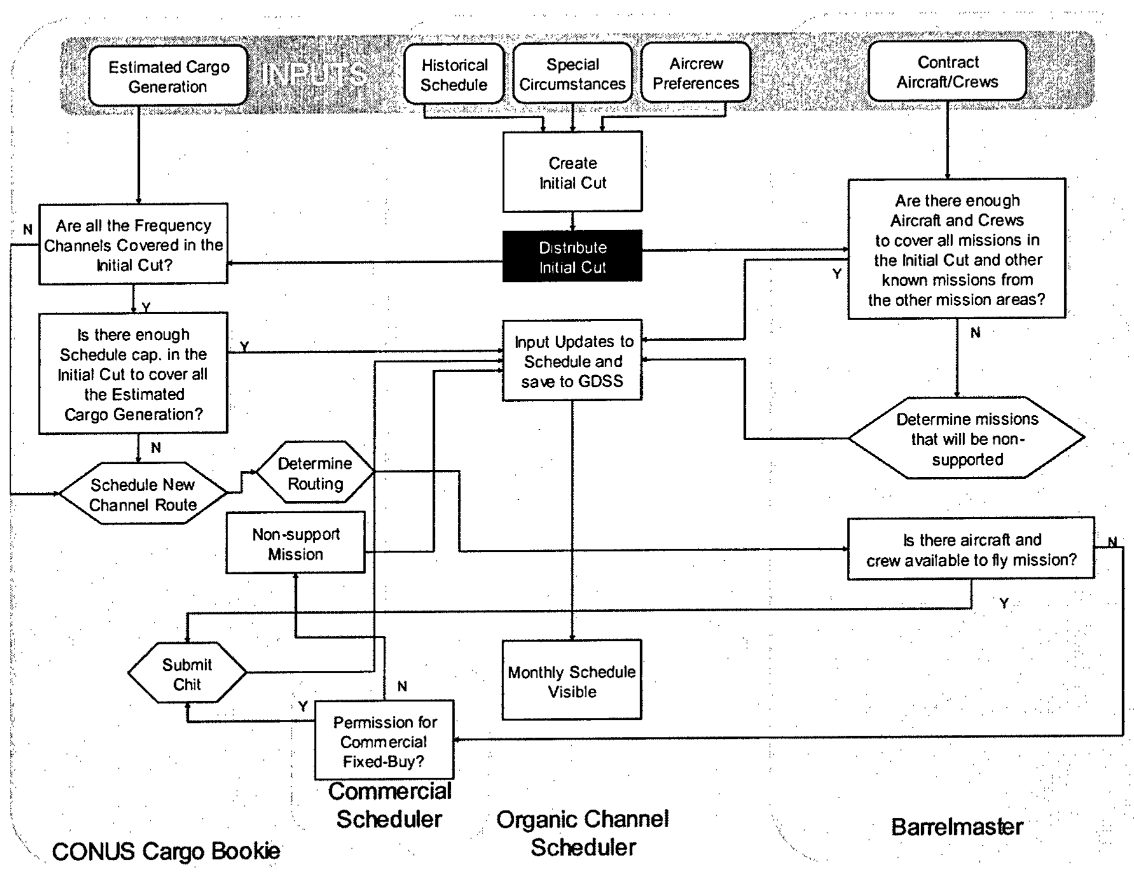


Figure 2-10: The current channel route scheduling process

2.2.5 Transition from the Planning Period to the Execution Month

Once the channel route schedule has been visible on GDSS for thirty days, it enters the execution month. The organic scheduler can still make updates to the schedule, but the floor becomes responsible for the execution of individual channel route missions beginning twenty-four hours before the mission begins and ending once the mission is completed. Because missions start and end at different times, the execution phase is a window that slides through the execution month as individual missions are executed. The twenty-four hour time frame is arbitrary, but is adequate for detailed mission planning and lets the floor prepare for future missions. Once missions enter the execution phase, the organic scheduler cannot make changes to the missions in the execution phase although the floor might coordinate changes with the organic scheduler who developed the schedule. *Figure 2-11* illustrates the evolution of a plan from the beginning of the planning period through the execution month.

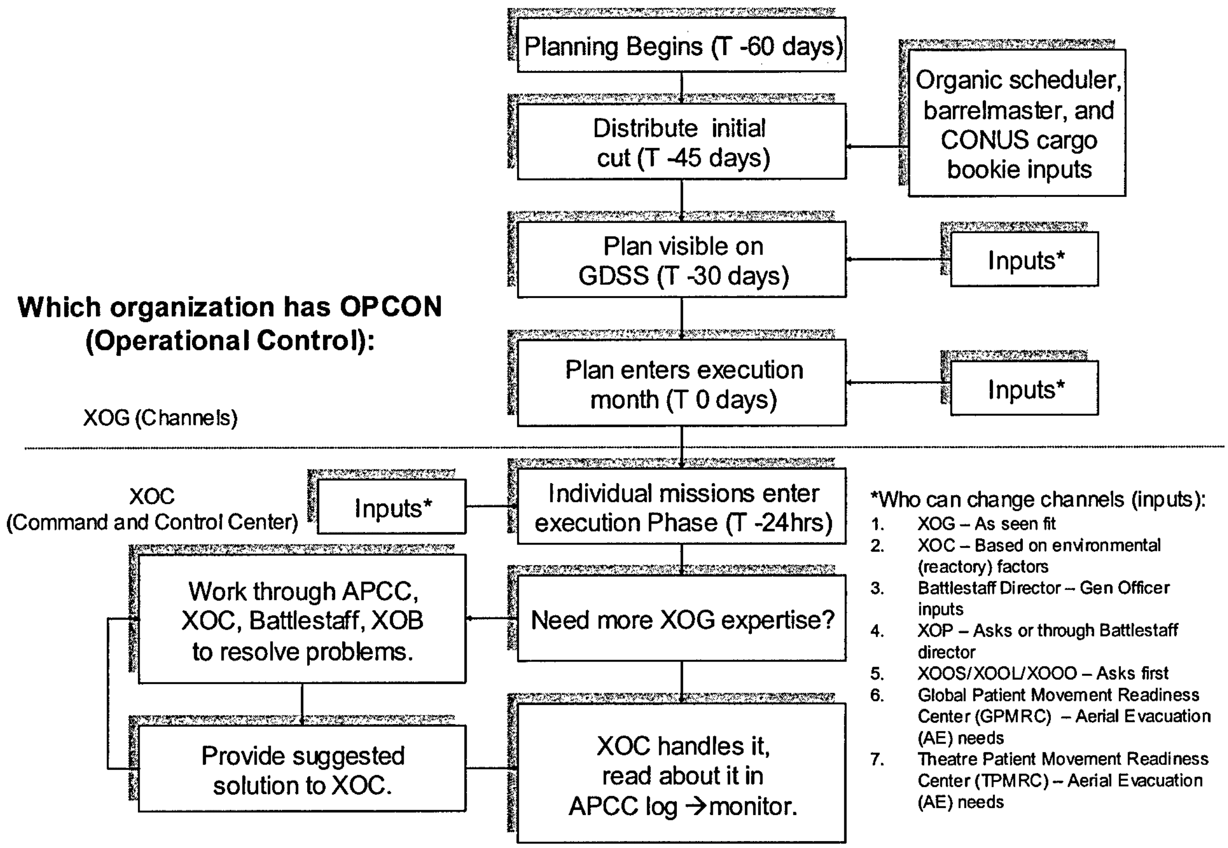


Figure 2-11: The channel route planning and execution process

2.2.6 The Execution Month

The execution of channel route missions is a dynamic and intense process that uses ad hoc methods and informal flows of information. The process is a mix of monitoring missions and reactionary replanning. Many organizations are responsible for monitoring and solving problems arising in the execution of missions that could not be foreseen in the planning period and that might overlap the organizations' responsibilities. The purpose of this section is to describe the current execution process of the channel route missions by describing the key players of all mission areas in the execution month and how they interact with the channel route schedule.

2.2.6.1 General Overview

During the execution month, especially the execution phase, reactionary changes are made to the channel route schedule. The floor, the CONUS and offshore cargo bookies, AE mission planners, the barrelmaster, and the commercial scheduler coordinate with the organic scheduler to make updates to the channel route schedule. Updates are required when the channel route schedule is disrupted. *Figure 2-12* is provided to show common sources that cause disturbances to the channel route schedule during the execution month. For example, consider a disruption that causes validated cargo to lose its airlift, leaving an excess of cargo at an aerial port. The CONUS and offshore cargo bookies find solutions to get the airlift needed for the excess cargo at CONUS and OCONUS APOEs, respectively. Because channel route missions usually begin at CONUS APOEs, the CONUS cargo bookie has few options and most likely has to wait until the next scheduled aircraft arrives at the APOE. However, the offshore cargo bookie can take a more active role in finding solutions at OCONUS APOEs, such as rerouting aircraft and finding opportunities to use spare capacity from the other mission areas. While the cargo disruptions occur in the execution phase, the CONUS and offshore cargo bookies might re-plan the channel route schedule beyond the execution phase.

The execution phase within the execution month combines monitoring and problem solving in real-time. The floor is the focal point for the execution phase and the organic scheduler can no longer make changes to the missions. The floor is organized into the command and control center, maintenance cell, Aerial Port Control Center (APCC), battlestaff, and AE cell. The command and control center is responsible for executing all missions, while the other divisions are representatives of outside organizations that support the command and control center. If disruptions do not arise in the channel route schedule, then the missions are executed as planned by the organic schedulers and there would be no need for the floor. However, this is unrealistic and the schedule needs continual updating during the execution phase as disruptions occur.

2.2.6.2 Participating Organizations in the Execution Month

This section presents the organizations that are involved in executing missions. The floor consists of the organizations that are responsible for missions during the execution phase. While the other organizations, such as the global channel operations and barrelmaster, play an indirect role in the execution phase, they play an important role during the execution month. In addition to presenting the organizations, this section will show how channel route missions might be disrupted.

Higher Mission Priorities
Aircraft Crew Needs
Aircraft Maintenance
Diplomatic Clearance (DIPS)
Unplanned Aerial Evacuations (AE)
Maximum on Ground (MOG)
Weather
Operating Hours
Cargo Handling Maintenance
Unpredicted Cargo Fluctuation

Figure 2-12: Common sources for disruptions during execution

2.2.6.2.1 The Floor

The floor consists of the agencies and representatives of agencies that have a direct participation in the execution phase. Agencies that actually "live" on the floor are the command and control center, APCC, AE cell, maintenance cell, and battlestaff. *Figure 2-13* summarizes the flow of information from a channel route mission perspective within the floor and other agencies that commonly interface with the floor.

2.2.6.2.1.1 Command and Control Center

The command and control center is the nerve center during the execution phase and is split into different cells on the floor by mission areas and aircraft types. The hierarchy of the command and control center is shown on *Figure 2-14*. The first level is the senior, who is considered the representative of the AMC commander, a general officer. Note that the AMC commander does not actually perform the job of senior, but that the senior has the same authority as the commander while on the floor. Below the senior are the different agencies of the floor: command and control center, APCC, AE cell, maintenance cell, and the battlestaff. Within the command and control center, two deputy duty officers (DDO) are responsible for specific mission areas. The mission areas are split into two categories. The first is Air Reserve (AR) and contingency. AR represents Air Force wings comprising of "citizen soldiers" that augment regular forces. The second is SAAM, channel, and other missions, such as exercises and JA/ATTs. Below the DDOs are the duty officers (DO), who are in charge of individual cells

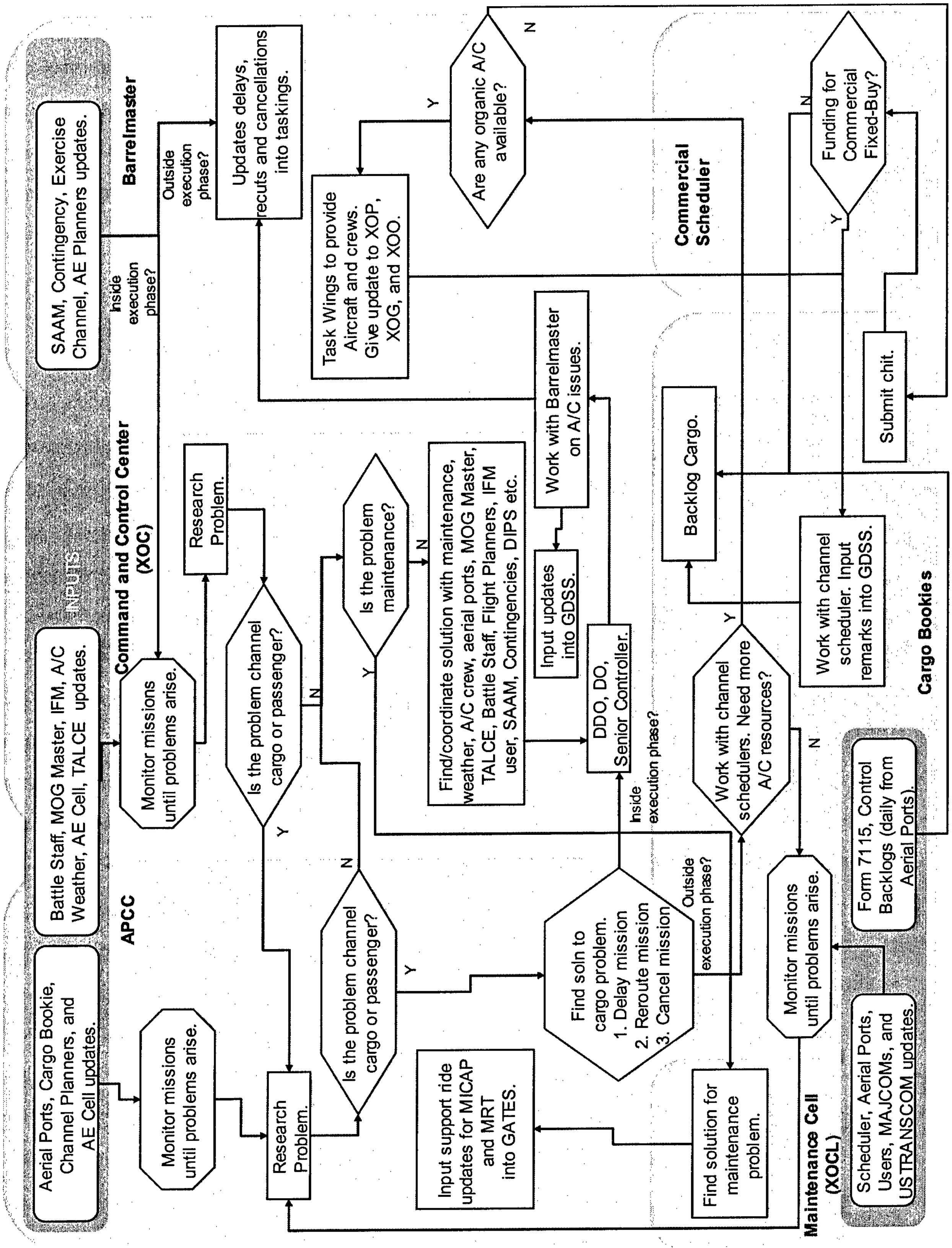


Figure 2-13: Flow of information from the perspective of channel route execution

within the command and control center. Each cell is responsible for a different aircraft type. This is a recent change, because the cells were previously organized by the departure points of the aircraft: the west and east cells. Within each cell, a lead controller is in charge of a team of controllers. The controllers interface with the AMC network through phone calls and a variety of database interfaces, such as IMF, CAMPs, and GATES. Once they are aware of problems, they use a series of checklist forms that provide guidelines to handle disruptions to the schedule. The checklist forms are based upon the official policies listed in the AFIs. Problems are solved at the lowest possible level with a report back to higher levels and outside agencies. The checklist forms also state the lowest level at which decisions can be made. For example, a controller may be allowed to delay an aircraft for two hours, but will have to get the senior's approval to cancel the mission.

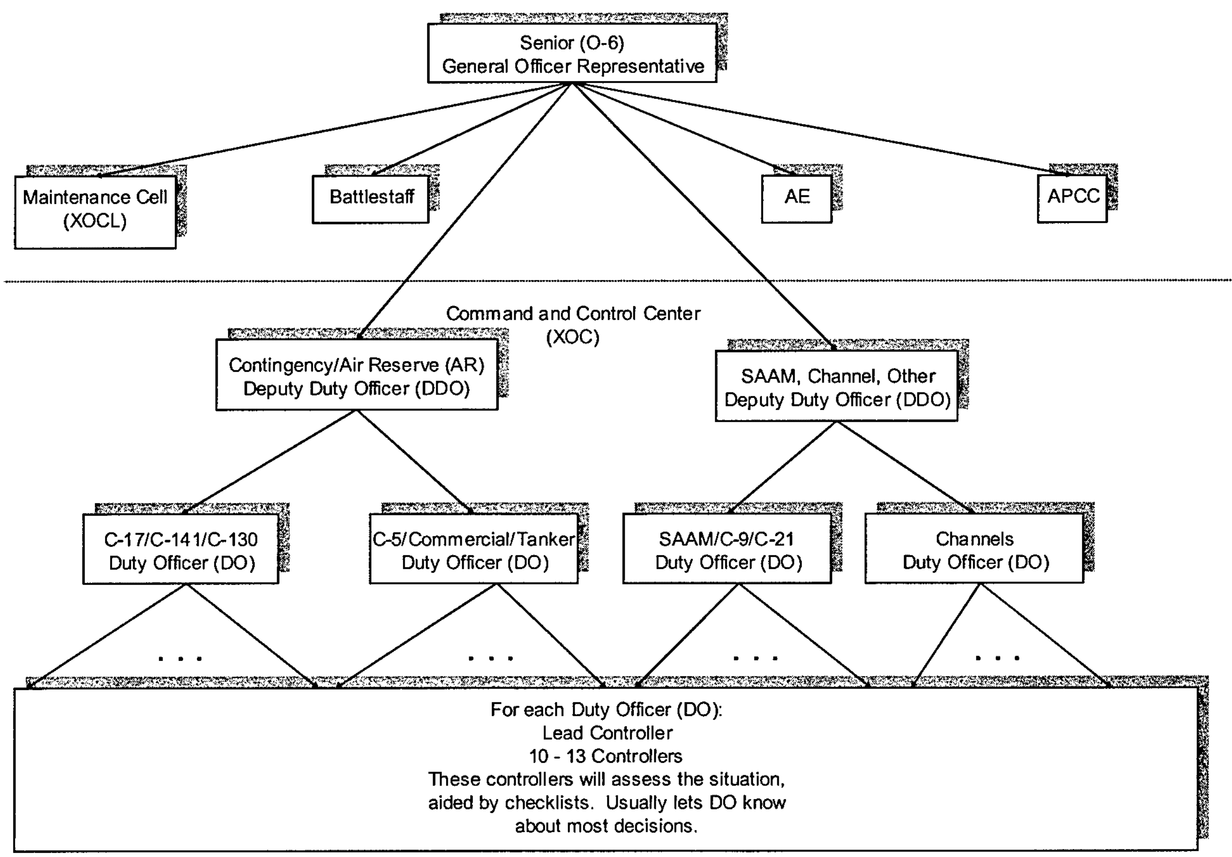


Figure 2-14: Command and control center hierarchy

While the command and control center is ultimately responsible for the execution of all missions in all mission areas during execution, it coordinates with other agencies on the floor to make decisions. For instance, if a maintenance problem occurs, the command and control center directs the problem to the maintenance cell, which has experts on maintenance problems. The command and control center might seek advice from agencies outside the floor when they are unable to solve the problem, such as the schedulers of the different mission areas. When the command and control center does make decisions and changes the current plan during the execution phase, they report back to the appropriate agencies outside of the floor to update them of the changes. The command and control center coordinates solutions regarding channel route missions with the APCC.

2.2.6.2.1.2 The Aerial Port Control Center

Functionally, the APCC is only responsible for the channel route cargo and passengers during the execution phase. The APCC reports events into GATES and works as an interface between the command and control center, maintenance cell, AE cell, offshore cargo bookie, CONUS cargo bookie, aircraft and aerial ports. The APCC closely monitors channel routes and records events into GATES in a real-time manner. Unlike the command and control center, which concentrates on efficient flow of aircraft, the APCC concentrates on efficient flow of cargo between aerial ports. While monitoring channel route missions, the APCC will commonly receive information about disruptions to channel route missions through phone calls or conversations with the command and control center, aerial ports, aircraft, aerial evacuation cell and maintenance cell. The APCC will then take this information and find a solution. Usually, the only direct change that the APCC will make is to delay an aircraft for less than 24 hours. For most other changes, the APCC will coordinate their solutions and actions with the CONUS and offshore cargo bookies. Once a solution has been found, APCC coordinates with the command and control center, which implements the solution within the execution phase, and the CONUS and offshore cargo bookies, who implement the solution outside the execution phase. If the disturbance is caused by a maintenance problem, the APCC will jointly find a solution with the maintenance cell and the offshore and CONUS cargo bookies.

2.2.6.2.1.3 The Battlestaff

The battlestaff operates in wartime situations and is used by high ranking general officers as a direct line to altering aircraft missions during the execution phase. In fact, many of the functions of the battlestaff mirror those of the command and control center to allow for the dynamic replanning of contingency missions. Because of the power behind the battlestaff, it can modify the channel route schedule at any time.

2.2.6.2.1.4 The Maintenance Cell

The maintenance cell coordinates the repair of aircraft. The cell is responsible for troubleshooting organic aircraft maintenance problems and finding solutions to problems within the AMC network. Because of the nature of AMC's mission, many aerial ports do not have permanent maintenance teams on location. Once an organic aircraft has a problem, the maintenance cell works with the aircraft crew to find a solution. Some aircraft aircrew have a *crew chief* that is knowledgeable on maintenance procedures. If the aircrew does not have a crew chief, then the maintenance cell might have to schedule delivery of a maintenance recovery team (MRT) and testing equipment to troubleshoot the broken aircraft. Once the problem has been discovered, the maintenance cell will schedule the delivery of spare aircraft parts to be flown to the broken aircraft. Besides the possibility that the broken aircraft might be flying a channel route mission, the missions that transport MRT, testing equipment and aircraft spare parts are considered to be mission capable (MICAP) requirements, which have a high level of priority in the AMC network. MICAP requirements might disrupt the channel route schedule because the maintenance cell commonly work with APCC to alter channel route missions for transportation.

The Air Force has an inventory of new aircraft, such as the C-17, and aging aircraft that were first produced in the 1950s, such as the C-5. The older aircraft are a challenge to keep well maintained. AMC uses a maintenance reliability factor based upon past statistics to assess the probability of an aircraft disrupting the schedule due to maintenance problems. Older organic aircraft tend to have a much lower maintenance reliability factor than newer aircraft.

2.2.6.2.1.5 Aerial Evacuation Cell

The AE cell is the AE missions' presence on the floor. The AE cell is responsible for ensuring that the missions that transport troops needing specific medical services at different bases within the CONUS are executed, and that enough aircraft are transporting sick and wounded troops OCONUS and HR are promptly flown back to the CONUS. While CRAF members perform most of the AE missions OCONUS, the commercial airline aircraft might become overloaded with a large number of passengers, or HR might need immediate transportation. In these cases, the AE cell will work the APCC and other mission areas to jointly use aircraft without disrupting the schedules of any mission areas. If the AE cell is unable to find a suitable solution, aircraft might be redirected from channel routes to support AE missions.

2.2.6.2.1.6 The MOG Master

The current MOG levels at an aerial port are dynamic due to the number of personnel on shift at the aerial port, the threat level to security, the number of aircraft currently at the aerial port, and the status of the aircraft and infrastructure. Therefore, the MOG master, a job rotated among the DOs, ensures that the aircraft missions will not exceed the MOG level at the aerial ports. To accomplish this task, the MOG master uses customized Excel macros that warn the MOG master of potential violations of MOG levels. The Excel macros do not suggest how to rectify MOG problems. In Chapter 4, we present a model that can find solutions to MOG problems.

2.2.6.2.2 Global Channel Operations

The CONUS and offshore cargo bookies, organic scheduler, AE mission scheduler, commercial scheduler, and the channel development and analysis division reside in global channels operations. Global channel operations are organized into two divisions, those that begin at the east coast APOEs and those that begin at the west coast APOEs. Each division has a CONUS cargo bookie, organic scheduler, and commercial scheduler. While the commercial scheduler works in either east or west channel operations, he/she is actually a representative of the commercial channel division. Once channel route missions leave the CONUS, they are no longer identified with their respective APOEs, so the offshore cargo bookie is organized under a separate air transportations operations division and is responsible for all cargo that is OCONUS. The AE mission scheduler physically resides in the AE division. The channel development and analysis division creates the sequence listing and monitors the performance of the divisions of the global channels operations. *Figure 2-15* shows the divisions of the global channel operations.

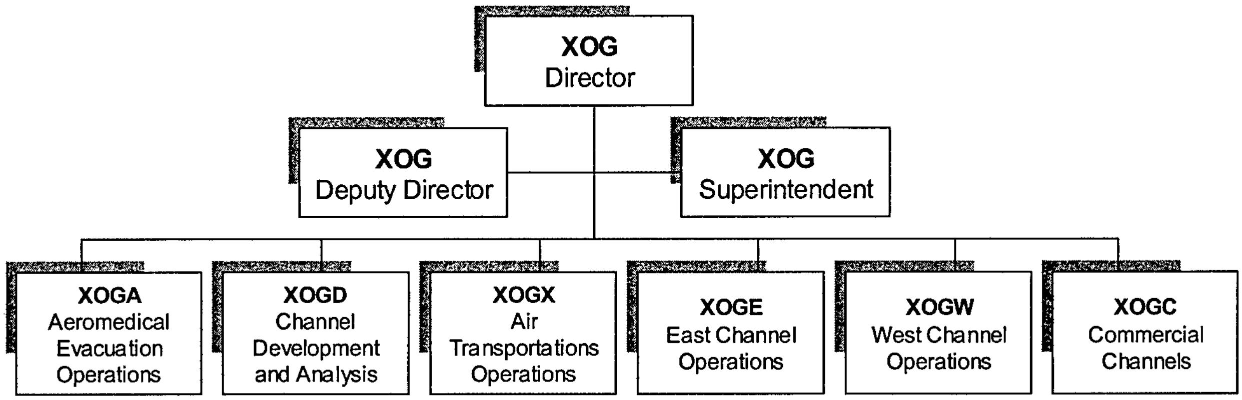


Figure 2-15: Global channel operations organizational chart

2.2.6.2.2.1 The Commercial Scheduler

The commercial scheduler manages the fixed-buy and expansion-buy contracts with the commercial airline industry. They work closely with commercial airlines to ensure routes are acceptable for the channel route schedule. When there is not sufficient organic and fixed-buy commercial aircraft during execution, the CONUS and offshore cargo bookies may request additional commercial airlift from the commercial scheduler. The commercial schedulers then negotiate and schedule expansion-buy contracts.

2.2.6.2.2.2 The CONUS Cargo Bookie

The CONUS cargo bookie schedules the shipment of channel route cargo that leaves CONUS APOEs by working closely with the organic scheduler during the second month of the planning period. The CONUS cargo bookie schedules cargo during the second month of the planning period and is then "on-call" during the execution month to ensure cargo is reaching its destination. If there is not enough airlift capacity to transport all channel route cargo away from the CONUS APOEs, the CONUS cargo bookie first requests additional organic aircraft from the barrelmaster. If the barrelmaster has no available aircraft, the CONUS cargo bookie requests an expansion-buy contract from the commercial scheduler. If the CONUS cargo bookie is denied an expansion-buy contract, then the cargo is backlogged until the CONUS cargo bookie can find a solution.

2.2.6.2.2.3 The Offshore Cargo Bookie

The offshore cargo bookie does not play a role in the planning period of the channel route schedule. Instead, the offshore cargo bookie alternates months between being *on the books* during an execution month and performing administrative duties for a month to support the offshore cargo bookie that is on the books. While on the books, the offshore cargo bookie is responsible for ensuring that all channel cargo at OCONUS aerial ports is scheduled to be transported. The offshore cargo bookie monitors cargo at aerial ports using GDSS, GATES, phone calls to aerial ports, and an APCC status report of cargo levels at aerial ports. When disruptions occur to the channel route missions, the offshore cargo bookie will find solutions to problems caused by the disruptions. The offshore cargo bookie implements the solutions by coordinating with the organic scheduler, barrelmaster, CONUS cargo bookie, APCC, DIPS office, and other AMC mission areas. There is no decision support tool to help the offshore cargo bookie find solutions and take into account all relevant information. They must use experience that they gained working in the APCC, intuition, and the database interface tools, following a notional guideline in the type of decisions that need to be made. *Table 2-4* shows the notional guideline that the offshore cargo bookie follows when making decisions. In Chapter 4, we present methods that can use the guideline in a decision support tool.

Offshore Cargo Bookie Re-planning Guideline (decisions ordered from the most to least desirable)
1) Use existing channel route missions (usually done by aerial ports)
2) Use existing missions of other AMC mission areas
3) Delay existing channel route missions
4) Reroute existing channel route missions
5) Reroute existing missions of other AMC mission areas
6) Switch aircraft missions
7) Purchase additional organic airlift
8) Purchase expansion-buy aircraft
9) Backlog cargo

Table 2-4: Notional offshore cargo bookie guideline for decision making

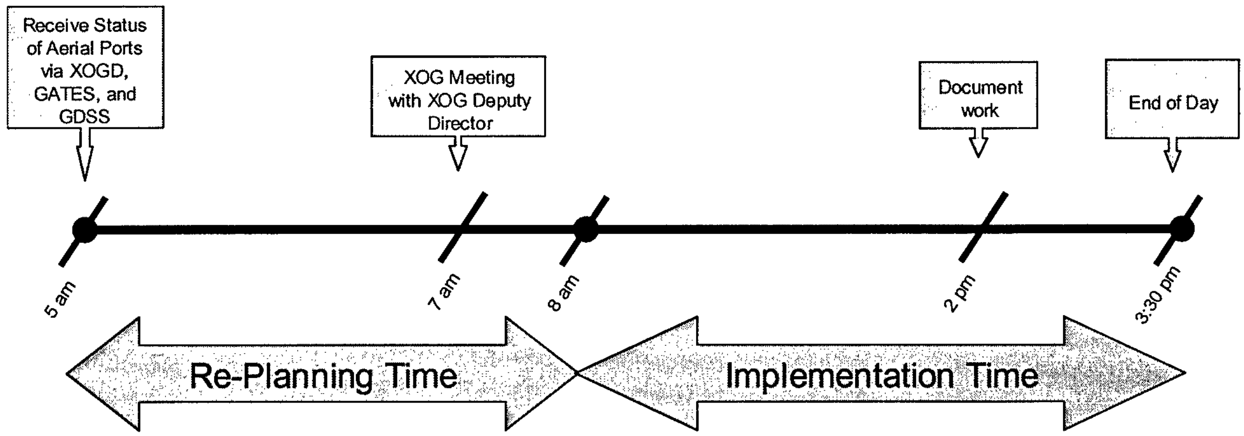


Figure 2-16: Offshore cargo bookie daily timeline

Information about channel cargo disruptions arrives to the offshore cargo bookie at 5 a.m. each morning in an APCC report via the channel development and analysis division. The offshore cargo bookie confirms the report and obtains the updated status of channel route cargo through GDSS, GATES, and phone calls to the aerial ports. Then, the offshore cargo bookie has two hours to find a solution before a 7 a.m. meeting with the XOG deputy director who gives approval to a final joint solution. The offshore cargo bookie spends the remainder of the day implementing the solution. When the offshore cargo bookie is on the books, he/she might learn about disruptions any time of the day through a cell phone call and might direct changes over the phone when an urgent problem must be solved. *Figure 2-16* shows the daily timeline of the offshore cargo bookie.

2.2.6.2.3 The Barrelmaster

The barrelmaster is responsible for allocating aircraft and crews among AMC's mission areas. The barrelmaster uses an Excel spreadsheet to monitor the allocation of aircraft and manually inputs the data from the spreadsheet into CAMPS. Once into CAMPS, the data feeds into GDSS. The barrelmaster is the liaison between the flying squadrons and AMC. The barrelmaster tasks the aircraft squadrons and works with the aircraft squadrons when changes need to be made to mission areas' schedules. The barrelmaster cannot alter aircraft assigned to the mission areas within ninety-six hours of execution without the approval of a general officer. The barrelmaster does not recognize the planning period and execution month, as he/she is only concerned whether aircraft are assigned to a mission area, not assigned, or in the execution phase. During channel route execution, the barrelmaster helps find solutions to aircraft maintenance and aircrew disruptions. The barrelmaster coordinates with the maintenance cell to repair aircraft and works with the aircraft squadrons to extend aircrew's mission hours or reposition aircrew.

2.2.6.2.4 Other Mission Areas

SAAMs, contingencies, exercises and JA/ATs mission areas play a role in channel route execution by causing disruptions and providing opportunities to move channel cargo that has been delayed due to a disruption. The other mission areas cause disruptions to channel route missions when there are not enough aircraft to fly all missions and the channel route missions are lower priority. Other mission areas might sometimes provide opportunities. SAAMs regularly have empty flight legs, because customers might only purchase the aircraft one-way. The offshore cargo bookie leverages empty flight legs as additional cargo space for channel route missions through communication with the SAAM scheduler, consisting of the SAAM scheduler sending to the offshore cargo bookie hand-made Excel files that show the empty flight leg information. This type of communication is not currently used between the offshore bookie and the contingency, exercises, and JA/ATs mission schedulers. Contingency missions are dynamic and the contingency mission scheduler uses grease boards for mission planning, inputting the contingency schedule into GDSS after some of the missions have been executed. As a result, the offshore bookie receives outdated information. The offshore cargo bookie might find opportunities in exercises and JA/ATs mission areas. In Chapter 4, we present methods that can be used to find these opportunities.

2.3 Motivation for Decision Support Tools

The purpose of this section is to outline the attributes of channel route execution that motivate the need for decision support tool concepts presented in later chapters.

2.3.1 Large Amounts of Information

Channel route execution is affected by many different divisions within AMC that change and update information. It is difficult to manually process the information, let alone finding good solution to channel route schedule disruptions. A suitable decision support tool can quickly gather information and process it to optimize re-planning of channel route schedules.

2.3.2 Urgency for Decision Making

Many of the decisions in channel route execution are time sensitive. During the execution phase, some decisions must be made within minutes to ensure smooth operation of the AMC network. Within the execution month, some decisions must be made within hours to help limit the disruptions to AMC's schedule. This is true of the offshore cargo bookie who must quickly find solutions to disruptions of channel route cargo. The time required for decision making does not easily allow for an analysis of alternatives. The longer AMC personnel wait to make decisions, the more outdated the decisions might become. A decision support tool can create many different options that allow a decision maker to compare the alternatives within a reasonable timeframe.

2.4 Summary

This chapter has introduced channel routes in the context of all AMC operations. Furthermore, this chapter has familiarized the reader with the current channel route planning and execution process and the challenges AMC faces during channel route execution. These challenges motivate the necessity of a decision support tool. The formulations and models developed in the remaining chapters are initially aimed at providing decision support to the offshore cargo bookie during the channel route execution.

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3 Network Models Background

The previous chapter described the current channel route execution process from an operational perspective. The purpose of this chapter is to describe the foundation for the mathematical models presented in Chapter 4. The concepts are presented for the reader who has had experience with mathematical programming.

This chapter begins with an overview of approaches to solving the multicommodity network flow problem by describing two general formulations: arc flow and path flow. Section 3.2 describes problems and associated solution techniques that are relevant to the problem and solution techniques described in Chapter 4, the first being service network design and the second being multi-airport ground-holding, a problem in air traffic control. The chapter concludes with a literature review of the composite variable concept found in Nielsen [24] and the re-planning problem facing commercial airlines.

3.1 Multicommodity Network Flow Problems

For multicommodity network flow (MCNF) formulations, we denote the network as $G(N,A)$, where A is the set of arcs and N is the set of nodes. In transportation problems, nodes represent physical locations on a map and arcs represent transportation resources in the physical system, such as trucks or aircraft, which travel between the nodes. A type of cargo transported

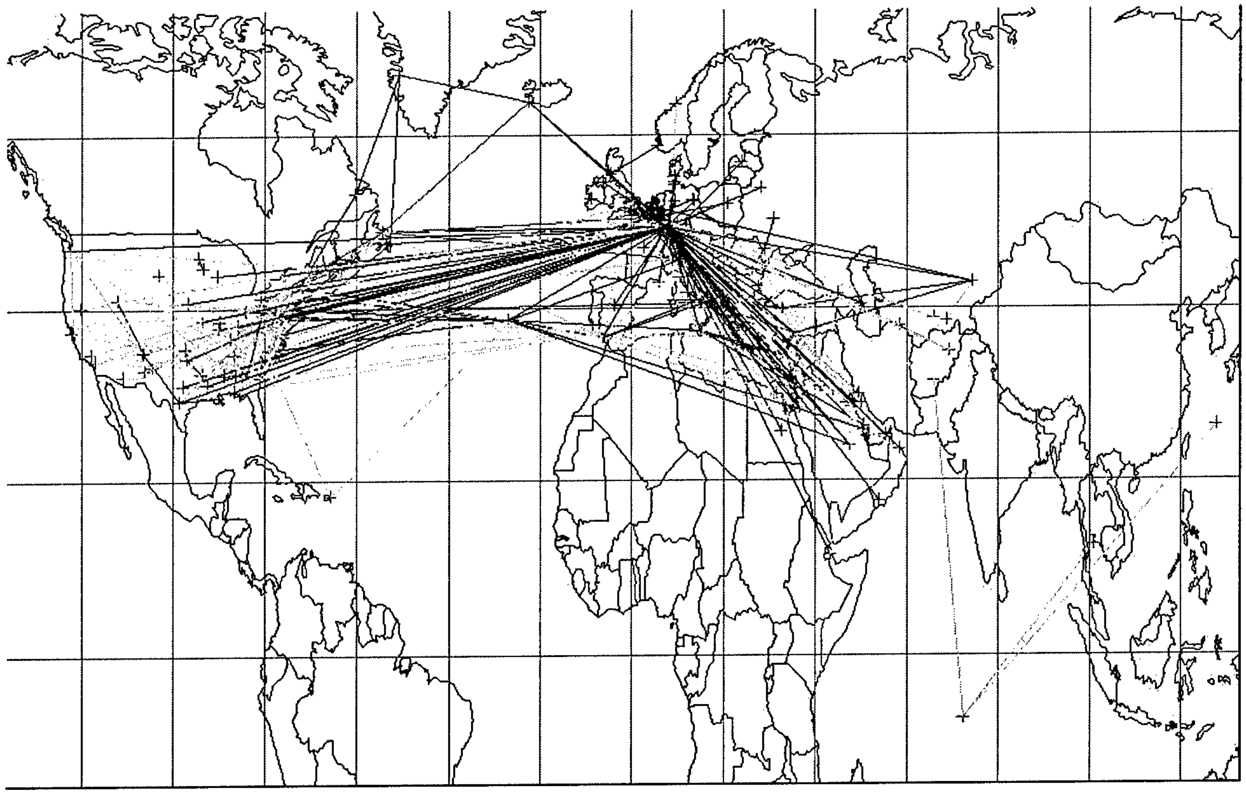

Figure 3-1: Air Mobility Command (AMC) network

between nodes through the arcs is called a commodity. An MCNF formulation optimally solves the assignment of commodities to arcs [1]. *Figure 3-1* shows an example of arcs and nodes in the AMC network.

Commodities can be classified by types with specified origins and destinations. For instance, aircraft engines and perishable goods may be classified as different types of commodities. If a commodity $k \in K$ departs from node $i \in N$, then node i is the origin node with a supply of $b_i^k > 0$. If a commodity arrives at node i, then node i is the destination node with a demand of $|b_i^k|$, where $b_i^k < 0$. Commodity k travels through the network by flowing through arcs $(i,j) \in A$, where $i, j \in N$. Let the amount of unit flow of commodity k through arc (i,j) be f_{ij}^k and the unit capacity of arc (i,j) be u_{ij}. A commodity flows through different arcs to get from the origin/supply node to the destination/demand node and the unit linear cost of flow for commodity k through arc (i,j) is denoted by c_{ij}^k. A feasible sequence of arcs through which commodity k can flow from origin to destination is a path $p^k \in P$. The cost c_p^k of the path p^k is the sum of the costs c_{ij}^k for all the arcs on the path.

The following sections describe two MCNF formulations that are based on either arcs or paths. The arc flow formulation assigns flows through individual arcs, while the path flow formulation assigns flows through paths.

3.1.1 Arc Flow Formulation

The decision variable x_{ij}^k in the arc formulation is the amount of commodity k assigned to arc (i, j). Let the origin and destination nodes for commodity k be denoted by *O(k)* and *D(k)*, respectively. When commodity k flows through node i and node i is neither a supply nor demand node, it is called a transshipment node. Let $b_i^k > 0$, $b_i^k < 0$, and $b_i^k = 0$ for commodity k's supply, demand, and transshipment nodes in balance of flow constraints. Ahuja et al. [1] present the following arc formulation and Nielsen [24] applies it to the channel route mission planning:

$$\text{MCNF-A=} \qquad \min \sum_{k \in K} \sum_{(i,j) \in A} c_{ij}^k x_{ij}^k \tag{3.1}$$

$$s.t. \qquad \sum_{k \in K} x_{ij}^k \le u_{ij} \qquad \forall (i,j) \in A, \tag{3.2}$$

$$\sum_{\{j:(i,j)\in A\}} x_{ij}^k - \sum_{\{j:(j,i)\in A\}} x_{ji}^k = \begin{cases} b_i^k > 0, \text{ if } i = O(k) \\ b_i^k < 0, \text{ if } i = D(k) \\ 0, \text{ otherwise} \end{cases} \qquad \forall i \in N, k \in K, \tag{3.3}$$

$$x_{ij}^k \ge 0 \qquad \forall (i,j) \in A, k \in K. \tag{3.4}$$

The objective function (3.1) minimizes the total linear cost of the flow throughout the network. Constraints (3.2) force the commodity flow over an arc to be less than the arc's capacity. Constraints (3.3) ensure balance of flow at the nodes with respect to each commodity. Constraints (3.4) ensure non-negative flow.

3.1.2 Path Flow Formulation

The decision variable x_p^k is the fraction of commodity k's flow assigned to path p. Paths model important aspects of transportation problems. For instance, AMC planners are concerned with the entire flight sequence (path) of an aircraft [24]. The individual flight legs (arcs) are decomposed from the flight path only after the flight path has been planned. A path will assign a commodity to a set of arcs. Let $\delta_{ij}^p = 1$ if arc $(i,j) \in A$ is included in path p, otherwise $\delta_{ij}^p = 0$. Let $q^k = |b_i^k|$, with node i being the origin or destination node for commodity k. Ahuja et al. [1] formulate the path-based MCNF and Nielsen [24] uses a version of the formulation in a column generation approach.

$$\text{MCNF-P} = \qquad \min \sum_{k \in K} \sum_{p \in P^k} c_p^k x_p^k \tag{3.5}$$

$$s.t. \qquad \sum_{k \in K} \sum_{p \in P^k} \delta_{ij}^p q^k x_p^k \le u_{ij} \qquad \forall (i,j) \in A, \tag{3.6}$$

$$\sum_{p \in P^k} x_p^k = 1 \qquad \forall k \in K, \tag{3.7}$$

$$x_p^k \ge 0 \qquad \forall k \in K, p \in P. \tag{3.8}$$

The objective function (3.5) minimizes the total cost of the commodity flow through the entire network. Constraints (3.6) force the total commodity flowing through an arc to be less than the capacity of the arc. Constraints (3.7) ensure that the total demand for each commodity is satisfied. Constraints (3.8) ensure nonnegative flow through all paths.

3.2 Service Network Design Problem

While the MCNF problem optimizes flow on a fixed network structure, network design problem (NDP) determines both the network structure and the flow of commodities on that structure. The NDP formulation has both path decision variables and design decision variables. The path decision variables are the same as the decision variables in the MCNF-P. A design decision variable decides whether or not an arc is introduced into the network. In this section we consider a specific NDP, called the service NDP (SNDP). A NDP is also a SNDP when the design decision variables are forced to have balance of flow. In other words, a transportation resource that arrives at node $i \in N$ must also depart that node. *Example 3-1* illustrates the use of both path and design decision variables.

Example 3-1: Consider the network in Figure 3-2 with six aerial ports – A,B,C,D,E,F, two aircraft, and a single dynamic commodity that must be transported from aerial port D to aerial port F. Aircraft 1 has an original flight sequence of A→C→ F, but could divert to aerial port D and aircraft 2 has an original flight sequence of B→E→ F, but could also divert to aerial port D. Then, the dynamic commodity has the following two paths:

D→E→F on Aircraft 2 and

D→C→F on Aircraft 1.

The model must select a single path for the dynamic commodity. The aircraft have original arcs and diverted arcs. In this case the aircraft have the following specific arcs:

A→C, A→D, D→C, C→F for aircraft 1 and

B→E, B→D, D→E, E→F for aircraft 2.

The model must select the arcs such that the aircraft fly legitimate flight routes. In this case, the original flight routes and the rerouted flight routes are legitimate.

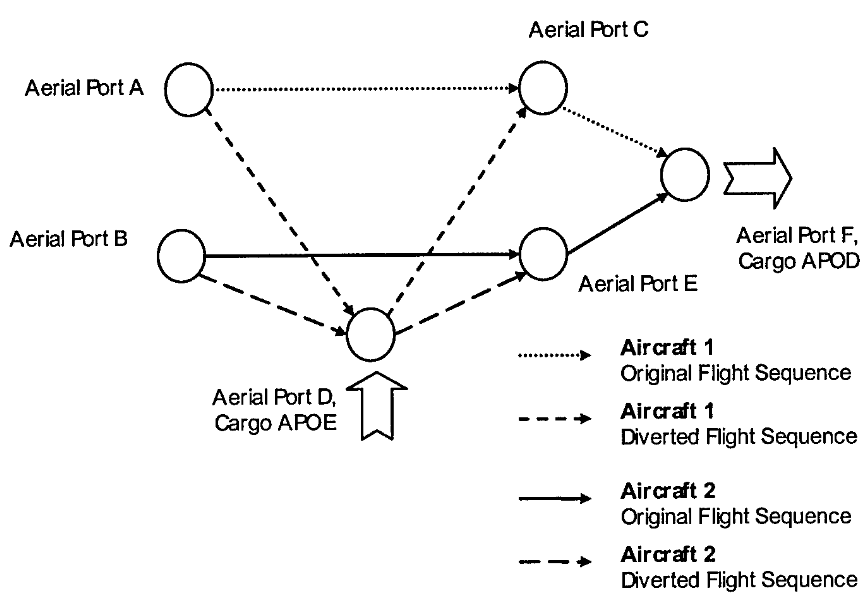

Figure 3-2: Example of a network design problem (NDP)

The SNDP formulation (SNDP-F) includes a set of capacity resources F that can be added to the network. Let d_{ij}^f denote the cost of capacity resource $f \in F$ being added to arc (i,j). If capacity resource $f \in F$ is added on arc $(i,j) \in A$ to the network then the binary decision variable $y_{ij}^f = 1$, otherwise $y_{ij}^f = 0$. Denote the capacity of resource f on (i,j) as u_{ij}^f.

Ahuja et al. [1], Magnanti and Wong [22], Armacost [5] and Nielsen [24] present the following NDP.

$$SNDP-F= \qquad \min \sum_{k \in K} \sum_{p \in P^k} c_p^k x_p^k + \sum_{f \in F} \sum_{(i,j) \in A} d_{ij}^f y_{ij}^f \tag{3.9}$$

$$s.t. \qquad \sum_{k \in K} \sum_{p \in P^k} \delta_{ij}^p b^k x_p^k \le u_{ij}^f y_{ij}^f \qquad \forall (i,j) \in A, \tag{3.10}$$

$$\sum_{p \in P^k} x_p^k = 1 \qquad \forall k \in K, \tag{3.11}$$

$$\sum_{\{j:(i,j)\in A\}} y_{ij}^f - \sum_{\{j:(j,i)\in A\}} y_{ji}^f = 0 \qquad \forall i \in N, f \in F, \tag{3.12}$$

$$x_p^k \ge 0 \qquad \forall k \in K, p \in P^k, \tag{3.13}$$

$$y_{ij}^f \in \{0,1\} \qquad \forall (i,j) \in A^f, \forall f \in F. \tag{3.14}$$

The objective function (3.9) minimizes the total cost of commodity flow and resource assignment. Constraints (3.10) force the total flow on each arc to be less than the capacity assigned to the arc. The convexity constraints (3.11) ensure that all of a commodity is transported, similar to constraints (3.7) in MCNF-P. Constraints (3.12) ensure balance of flow for the capacity resources. The non-negativity constraints (3.13) keep the path decision variables non-negative. Constraints (3.14) define the resource capacity decision variables to be binary.

The SNDP-F has three potential disadvantages. First, this formulation has a weak LP relaxation, because the constraints (3.10) aggregate the capacity of multiple resources allowing the possibility of y_{ij}^f being highly fractional. Second, there are an exponential number of potential paths. For instance, *Figure 3-3* presents a small network where four additional nodes cause an increase from sixteen to sixty-four possible paths. An exponential number of paths quickly causes models of real systems to become too large to solve. Third, the resource balance-of-flow constraints magnify the fractionality problem. We present a formulation in this thesis based on the SND-F, but we use methods that help alleviate these potential disadvantages.

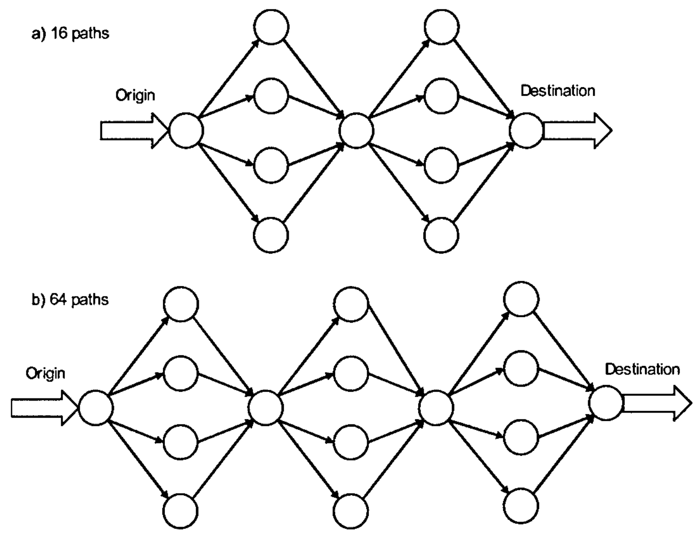

Figure 3-3: Example of a network with exponential number of paths

3.3 Air Traffic Flow Management

Bertsimas and Stock propose a method for solving the Multi-Airport Ground-Holding Problem (MAGHP) [8]. The MAGHP considers delaying commercial aircraft on the ground to reduce airspace congestion at airports. During the 1990s, congestion at airports and airspace was reaching unprecedented levels in the United States and Europe, costing airlines millions of dollars. Much of the cost was due to lost customer goodwill, expense in re-planning the airline's schedule, and air delay costs. This cost motivated efficient solution methods for the MAGHP.

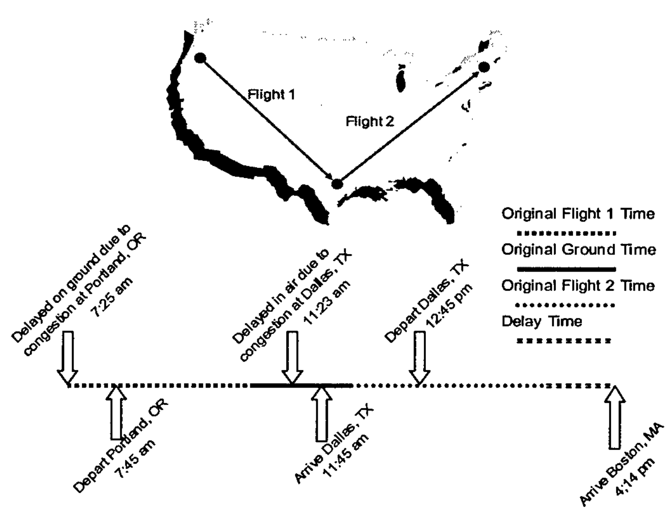

Figure 3-4: The effects of congestion on a hypothetical aircraft

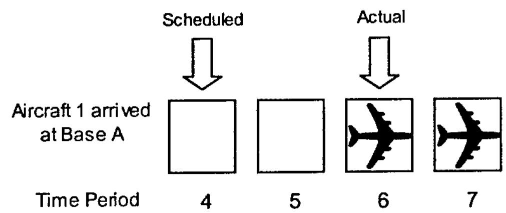

Figure 3-5: Multi-airport ground-holding problem formulation (MAGHP-F) decision variable

Example 3-2: Suppose Aircraft 1 in Figure 3-5 is scheduled to arrive at airport A during time period 4. However, aircraft 1 is allowed to be delayed up to three time periods. If aircraft 1 has arrived at airport A by time periods 6 and 7, then we know that Aircraft 1 has arrived during time period 6.

Bertsimas and Stock's MAGHP formulation (MAGHP-F) assigns ground holds to commercial airline flights when the aircraft are on the ground at airports, so that the system-wide congestion can be minimized. The idea is that if aircraft can be strategically delayed on the ground, then the costs of delays in the air are reduced and safety is enhanced. The formulation is unique from its predecessors in that its binary decision variables do not explicitly represent where an aircraft will be at a particular moment. Rather, they decide if an aircraft has arrived/departed or not arrived/not departed an airport at a certain time. Constraints are used in the MAGHP-F to ensure that once a flight has arrived at its arrival airport at a certain time period that all decision variables with subsequent time periods relating to the arrival of the same flight have also arrived. By defining variables as "arriving by time period t" rather than "arriving at time period t," Bertsimas and Stock had formulated the problem with a stronger LP relaxation than others in literature [8].

Before the formulation is presented, we must introduce new notation. For convenience, we rewrite previous notation here as needed.

<u>Network Structure</u>

F	set of flight legs;
C	set of flight legs that continue onto other flight legs;
K	set of all airports;
T	the set of time periods that an aircraft can be delayed;

Data

T_f^a	feasible time periods that flight leg f can arrive at its respective airport;
T_f^d	feasible time periods that flight leg f can depart from its respective airport;
$D_{k,t}$	departure capacity of airport k at time t;
$A_{k,t}$	arrival capacity of airport k at time t;
o_f	turnaround time of an airplane after flight leg f;
r_f	scheduled arrival time period for flight leg f;
h_f	scheduled departure time of flight leg f;
c_f^g	cost of holding flight leg f for one time period on the ground;
c_f^a	cost of holding flight leg f for one time period in the air;

Decision Variables

$$w_{f,t}^1 = \begin{cases} 1, & \text{if flight leg } f \text{ departs from its arrival base by time period } t. \\ 0, & \text{otherwise.} \end{cases}$$

$$w_{f,t}^2 = \begin{cases} 1, & \text{if flight leg } f \text{ arrives at its arrival base by time period } t. \\ 0, & \text{otherwise;} \end{cases}$$

MAGHP-F=

$$\min \sum_{f \in F} \left[(c_f^g - c_f^a) \sum_{t \in T_f^d} t(w_{f,t}^1 - w_{f,t-1}^1) + c_f^a \sum_{t \in T_f^a} t(w_{f,t}^2 - w_{f,t-1}^2) + (c_f^a - c_f^g) h_f - c_f^a r_f \right] \quad (3.15)$$

s.t.

$$\sum_{f: t \in T_f^d} (w_{f,t}^1 - w_{f,t-1}^1) \le D_{k,t} \qquad \forall k \in K, t \in T, \quad (3.16)$$

$$\sum_{f: t \in T_f^a} (w_{f,t}^2 - w_{f,t-1}^2) \le A_{k,t} \qquad \forall k \in K, t \in T, \quad (3.17)$$

$$w_{f,t}^2 - w_{f,t-(r_f-h_f)}^1 \le 0 \qquad \forall f \in F, t \in T_f^a, \quad (3.18)$$

$$w_{f,t}^1 - w_{f',t-o_{f'}}^2 \le 0 \qquad \forall (f', f) \in C, t \in T_f^d, \quad (3.19)$$

$$w_{f,t}^1 - w_{f,t-1}^1 \ge 0 \qquad \forall f \in F, t \in T_f^d, \quad (3.20)$$

$$w_{f,t}^2 - w_{f,t-1}^2 \ge 0 \qquad \forall f \in F, t \in T_f^a, \quad (3.21)$$

$$w_{f,t}^1, w_{f,t}^2 \in \{0,1\} \qquad \forall f \in F, t \in T. \quad (3.22)$$

The objective function (3.15) minimizes the total delay cost derived from both air and ground delays. Constraints (3.16) force the total number of flights departing from an airport to be less than the departure capacity of the airport. Likewise, constraints (3.17) force the total flights arriving at an airport at a specific time to be less than the arrival capacity of the airport. The first set of connectivity constraints (3.18) ensure that a flight does not arrive at its arrival airport until it has left its departure airport and flown at least its scheduled flight time. The second set of connectivity constraints (3.19) ensure that each aircraft that arrives at an airport with a subsequent flight leg will not depart on that leg until it has arrived at the airport and remained on the ground at the airport for at least its scheduled ground time. Constraints (3.20) and (3.21) ensure that if a flight that has arrived or departed an airport will keep that status for the remaining time periods. Finally, binary constraints (3.22) ensure that the decision variables take the values of zero or one.

3.4 Channel Route Schedules

Nielsen applied a *composite variable* formulation to the development of the channel route schedule [24]. The composite variable formulation has a stronger LP-relaxation than conventional models and has the ability to handle AMC's complex operational rules. Although we do not explicitly use composite variables, we do use concepts from composite variables in designing our models. This section will give a general overview of Nielsen's approach.

Nielsen uses a composite variable formulation to allocate and route aircraft optimally to transport channel route cargo. The formulation could be used to create a decision support tool for organic schedulers in developing the initial cut of AMC's monthly channel route schedule. A composite variable combines multiple decisions into a single variable. To create composite variables, Nielsen heuristically combines cargo loadings with aircraft routes that satisfy AMC operational rules, such as aerial port restrictions, crew rest times and range of aircraft. Composite variable creation begins by generating *flight sequences* of aerial ports that "an aircraft will visit during a channel route mission" [24]. The flight sequences are then used to create *generic missions* by combining them with a type of aircraft and generic routing times that specify the times of day but not the specific days. Nielsen then creates *single-route composite missions* by combining the generic missions with a single validated cargo shipment. If an aircraft in a single-route composite mission has sufficient capacity to transport all of the customer's cargo, then the single-route composite mission will become a *single route composite variable*. However, if an aircraft does not have sufficient capacity to carry all of the customer's cargo, then aircraft are added to the single-route composite mission to become *multiple-route composite missions* until there is sufficient capacity to carry all of the customer's cargo. Once there is sufficient aircraft capacity in the multiple-route composite mission, it will become a *multiple-route composite variable*. *Figure 3-6* is Nielsen's overview of his composite variable creation heuristics [24].

Nielsen uses an IP to select an optimal subset of all the single-route and multiple-route composite variables. Because the heuristics ensure that the single-route and multiple-route composite variables remain feasible in each step of their creation, the IP does not need to explicitly enforce many of AMC's operational rules. The structure of the IP can remain the same even if operational rules change because the changes can be integrated into the composite variable creation heuristics. The creation of arcs and paths in Chapter 4 of this thesis uses Nielsen's concept of dealing with AMC's complex rules and allowing the IP to remain constant.

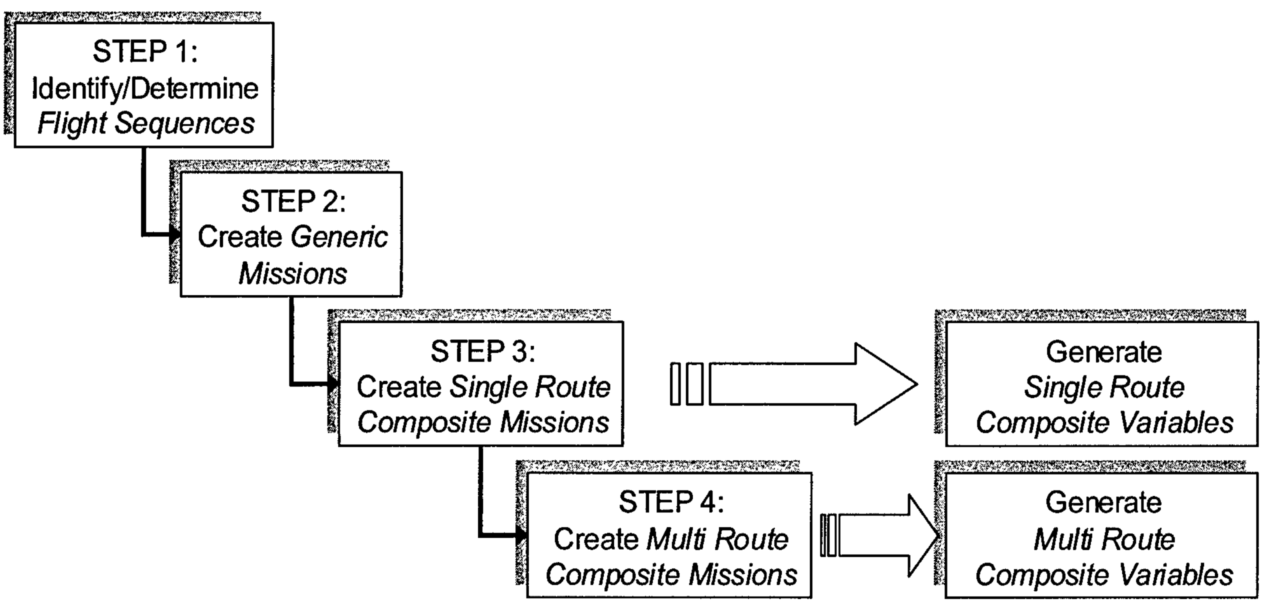

Figure 3-6: Nielsen's [24] composite variable generation steps

3.5 Commercial Airline Schedule Re-Planning in Real-Time

Research on schedule re-planning in real-time of transportation networks using optimization methods is relatively new and has focused primarily on the commercial airline industry. Airlines have small profit margins and large costs, so small improvements in recovering from disruptions in operations can reap large rewards. Subjective tradeoffs of conflicting goals and time restrictions are two challenges associated with re-planning in real-time. In the airline industry, operators must quickly solve disruptions to the schedule by canceling or delaying flight legs, with a tradeoff between short-term profits and customer goodwill. While the airline industry has different operational rules than AMC, there are many similarities, such as a need for bases, maintenance teams, and schedule recovery from disruptions in operations. While we do not use the formulations of the authors in this section, they present concepts that we use to approach the problem of schedule execution at AMC.

Research has focused on aircraft, crew, and/or passenger schedule recovery from disruptions. We use the dedicated aircraft recovery problem (DARP) which is defined by Løve and Sørensen [20] as a disruption to the original flight schedule that is solved by canceling flights, delaying flights, or aircraft swapping, which is the switching of two aircraft that fly two different flight legs. They define the dedicated crew recovery problem (DCRP) as the delaying of crew, placing crew on standby, using standby crew, swapping crew assignments, and transporting crew to find a better crew schedule. Bratu [9] defines the dedicated passenger recovery problem (DPRP) as minimizing the disruptions in the passenger schedule and is solved using the same techniques to solve DARP and DCRP. DARP, DCRP, and DPRP can be integrated, but it is difficult to solve as one problem. The literature tends to focus on DARP as the base problem and extends it with DCRP or DPRP. We describe now the chronological development of airline schedule execution models.

Teodorović and Stojković [27] solve an integrated DARP and DPRP using a lexicographic optimization formulation, which uses two prioritized objective functions. The first objective function maximizes the number of flights that continue on as scheduled (i.e., minimizes the number of cancellations) and the second objective function minimizes total passenger delay. The formulation is solved using a dynamic programming heuristic that quickly finds a near optimal solution [27]. In later research, Teodorović and Stojković integrate DCRP into their solution method [28].

Jarrah et al. [18] propose two separate mathematical programming models to solve DARP, one using flight delays and the other allowing cancellations. The objective functions minimize the costs involved in making changes to the original schedule. This includes delay and cancellation costs, costs associated with using aircraft not originally scheduled (surplus aircraft) and flying aircraft empty. The models are solved using network shortest path procedures.

Cao and Kanafani [10] extend the work of Jarrah et al. [18] by formulating the combined cancellation and delay model (CCD). The model only uses two constraints and solves quickly but has an intricate objective function that is the total revenue minus the swapping and delay costs. The cancellation costs are implied by the fact that a cancelled flight will receive no revenue.

Thengvall et al. [29] propose a mathematical model that can be solved using off-the-shelf optimization software. The objective function is to maximize an artificial "profit" function which is based upon revenue, delay costs, and protection arcs. They use "protection arcs" to combine multiple flights of a single aircraft, which will have a higher profit value than the summed profits of the individual flights. In this way, the authors are able to discourage drastic deviations from the original schedule and imply cancellation costs. However, the authors admit that "it is virtually impossible for airlines to provide accurate cost figures in real-time" [29].

Clarke [11] solves DARP using aircraft delays and cancellations in a mathematical programming framework with DCRP included as operational constraints. The objective is to maximize the operating profit which is defined as the total revenue minus the aircraft routing costs and cancellation flight costs (including lost revenue). Clarke solves his formulation using three different approaches: two greedy heuristics and an optimization-based procedure. His models require much human interaction.

Løve and Sørensen attempted to implement the CCD model but found the model to be "mathematically inoperable" [20]. As an alternative, they use iterative local search and steepest ascent local search heuristics to solve DARP quickly. The heuristics are used to attempt in optimizing an objective function that is linearly dependent on the revenue of the flights minus the costs of delaying and canceling flights. The objective function relies on the actual revenues and costs of the flights; however, this information is not known until weeks after the flights have been executed. Hence, multipliers, that scale the estimated revenue value to prioritize the delays and cancellations of particular aircraft, are used in the objective function. Løve and Sørensen also outline how they could use their techniques to solve the integration of DARP and DCRP, but do not actually solve it.

Bratu focuses on the trade-off between "airline resource operating costs and passenger schedule reliability" [9]. Airline resource operating costs are assumed to be well-defined, but passenger costs and the effects on customer goodwill are less understood, which motivates Bratu to explore passenger schedule reliability using new metrics and a passenger delay calculator (PDC) algorithm. PDC can be used to evaluate solutions of DARP to quantify the delay effects of solutions on passengers. Bratu also proposes optimization methods that integrate DARP, DPRP and DCRP.

3.6 Summary

In this chapter, we described the foundation for the mathematical models presented in Chapter 4. First, we overviewed the approaches to solving the multicommodity network flow problem by describing two general formulations: arc flow and path flow. Second, we described problems and associated solution techniques that are relevant to the problem and solution techniques described in Chapter 4, the first being service network design and the second being multi-airport ground-holding, a problem in air traffic control. Finally, we presented a literature review of the composite variable concept found in Nielsen [24] and the re-planning from disruptions in real-time operations found in the commercial airline business. In Chapter 5, we will use the concepts in this chapter and modify the service network design and multi-airport ground-holding solution techniques to formulate our models.

4 Functional Analysis and Modeling Approach

In Chapter 2, we presented an operational background on AMC and in Chapter 3, we presented a technical background and literature review on relevant models. In this chapter we present a functional analysis of the offshore cargo bookie decisions and explain the modeling approaches that can be developed into an offshore cargo bookie decision support tool. We analyze offshore cargo bookie decisions and show how the decisions can be modeled mathematically. The offshore cargo bookie process as a whole is then decomposed and we present two models and heuristics that are building blocks in this decomposition. The first model finds solutions to disruptions in the channel route schedule using a combination of transloading cargo, leveraging opportunities in other mission areas' schedules and rerouting aircraft. The second model finds solutions to disruptions due to violations of MOG constraints by strategically delaying aircraft at aerial ports. The chapter finishes with a discussion of a third model and discusses heuristics that can combine the three models.

4.1 The Offshore Cargo Bookie Process

The goal of the offshore cargo bookie is to keep channel route cargo flowing through OCONUS aerial ports, so he/she finds solutions to problems caused by cargo flow disruptions. The offshore cargo bookie follows a notional guideline of priorities for making decisions. In this

Added cargo: aircraft breaks down, cargo underestimated, rejected diplomatic clearance, channels lose aircraft to other mission areas
Added aircraft: aircraft fixed, cargo cancelled, cargo overestimated, other mission areas cancel missions
MOG Limits: the number of aircraft allowed at an aerial port is exceeded

Figure 4-1: A classification of disruptions

section we first classify cargo and disruptions, and then we analyze each decision in the notional guideline.

4.1.1 The Classification of Disruptions

From the perspective of the offshore cargo bookie, there are three general categories of disruptions (see *Figure 4-1*). The first category is *added cargo*, which occurs anytime unexpected channel route cargo enters the AMC network that has no scheduled airlift. Examples of added cargo disruptions include: aircraft scheduled to fly channel route missions are lost to other mission areas and cargo arriving at an aerial port is underestimated. Added cargo is considered an undesired disruption, and the offshore cargo bookies must find solutions to transport the added cargo. The second category of disruptions is *added aircraft*, which occurs when additional airlift that is not scheduled enters the AMC network. Examples of added aircraft include aircraft being repaired ahead of schedule and other mission areas canceling missions. Although this disruption is a change in the channel route schedule, it provides opportunities for the offshore cargo bookie to solve an added cargo disruption. The final disruption category is *MOG limits*. Although this disruption directly affects the MOG master and not the offshore cargo bookie, it might delay aircraft flying channel route missions. *Example 4-1* illustrates a MOG limits disruption and a possible solution. The offshore cargo bookie does not have a tool to analyze the effects of MOG constraints on their decisions. It is important to note that the three categories of disruptions occur at aerial ports, making the network models of nodes and arcs presented in Chapter 3 relevant in solving the disruptions.

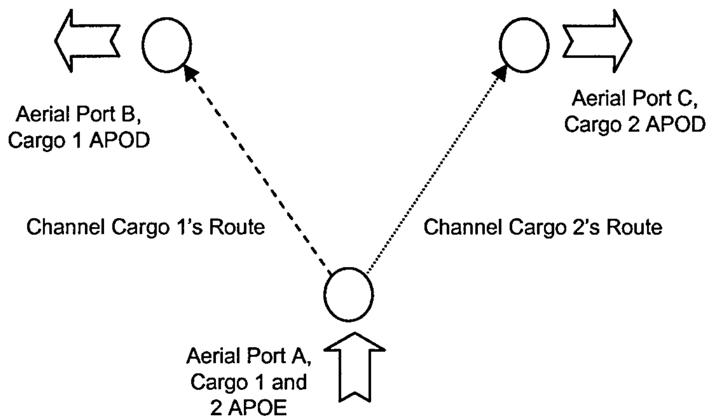

Figure 4-2: An example of a MOG Limit Disruption

Example 4-1: *Suppose two sets of channel route cargo, having the same weight and classification and not being HAZMAT, must be transported with cargo 1 traveling from aerial port A to aerial port B and cargo 2 traveling from aerial port A to aerial port C, as shown in Figure 4-2. Now suppose that cargo 1 is awaiting airlift due to an added cargo disruption while cargo 2 has a scheduled flight. However, aerial port C has exceeded its MOG limit for an indefinite amount of time. Therefore, it might be possible to reduce the total customer wait time by using cargo 2's airlift to transport cargo 1.*

4.1.2 Classification of Commodities and Aircraft Capacity

A commodity type is classified by the weight of the commodity and its origin-destination pair. This is an accurate representation of AMC's operations, because the standardized 463L crate system does not limit the variety of cargo that can be combined on a single crate. AMC also tries to combine cargo on the same crates that have the same APOE and APOD. A commodity has an *Available to Load Time* (ALT), which is the earliest the commodity is scheduled to be ready for loading onto an aircraft at its APOE. The *promised time* of a commodity represents the tentative time that a commodity will arrive at its APOD.

At this point, we create two definitions to support our description of disruptions in the AMC network. We define a *dynamic commodity* as a commodity that enters the AMC network from an added cargo disruption. The *residual capacity* of an aircraft is the total capacity of an aircraft minus the amount of cargo that is originally scheduled to be transported by the aircraft.

In the case of an added aircraft disruption, the additional aircraft have a residual capacity equal to their total capacity. When translating the AMC network into a network model, we identify dynamic commodities as our commodity flow and residual capacity as our transportation resource.

4.1.3 Notional Guideline for Offshore Cargo Bookie Decisions

In this section, we revisit the notional guideline that the offshore cargo bookie uses in making day-to-day decisions to find solutions to added cargo disruptions (see *Table 2-4*) and explain how we incorporate them into the models we present in §4.2. Note that some problems caused by disruptions cannot be solved by all decisions. The guideline serves as a ranking in decreasing order of desirability for handling problems caused by disruptions to the channel route schedule.

1. Use existing aircraft scheduled to fly channel route missions. If given a choice, the offshore cargo bookie does not want to impose additional disruptions on the channel route schedule. If residual capacity is scheduled to arrive at an aerial port that has an added cargo disruption, the offshore cargo bookie might not have to impose additional disruptions. Because the aerial ports are responsible for managing cargo at their own location, they might load dynamic commodities onto aircraft with the correct destination without consulting the offshore cargo bookie. However, the aerial ports might not optimally allocate dynamic commodities to residual capacity from the perspective of the entire AMC network. The offshore cargo bookie is in a position to allocate dynamic commodities to residual capacity optimally in the entire AMC network. We incorporate this decision into our model by considering the residual capacity of existing channel route missions.

2. Use existing aircraft of other mission areas. The offshore cargo bookie currently uses aircraft from SAAMs that have entire flight legs empty. There is also potential to use aircraft from exercises, JA/ATs, and possibly contingencies (if the data can be made available). The decision to use aircraft of other mission areas is less desirable than using aircraft from channel route missions because the offshore cargo bookie has less control over these aircraft and is at the mercy of changes and cancellations in the other mission areas' schedules. As in using existing aircraft scheduled to fly channel route missions, we consider the residual capacity of other mission areas in our model.

3. Delay aircraft scheduled to fly channel route missions. This decision is often made as a response to short-lived disruptions in the channel route schedule such as minor maintenance problems or weather. If the disruption becomes long-lived, then it can be considered an added cargo disruption. Delays inherently occur in the AMC network and the APCC (see §2.2.6.2.1.2) might delay aircraft without the guidance of the offshore cargo bookie when monitoring channel route missions on a minute-by-minute basis. Once the offshore cargo bookie is informed of the delay, he/she might decide to find an alternate solution, especially if the delay has a high probability of becoming long-lived, or he/she might simply decide to continue the delay. We incorporate channel route mission delays into our models directly when having aircraft delayed on the ground to ensure MOG compliance and indirectly when deciding how long aircraft wait at an APOE for a commodity's ALT.

4. Reroute aircraft scheduled to fly channel route missions. The offshore cargo bookie has the ability to reroute aircraft scheduled to fly channel route missions to relieve cargo backlogs at aerial ports. The offshore cargo bookie negotiates with the barrelmaster for rerouting organic aircraft and the commercial scheduler for rerouting commercial aircraft, who both ensure that the reroutes comply with aircraft and aircrew constraints. We integrate this decision in our models by heuristically creating additional arcs that represent the rerouting of aircraft.

5. Reroute aircraft of other mission areas. This is less desirable for the offshore cargo bookie than rerouting channel route aircraft because the other mission areas might be unable or unwilling to allow channels to have control of their aircraft routes. For example, SAAMs are unable to change the route of certain legs of its aircraft because the customer has been guaranteed specific routes. Because the possibility still exists that other mission areas might be willing to negotiate with the offshore cargo bookie, we include this decision to increase the offshore cargo bookie's options. Just as in rerouting channel route aircraft, we heuristically create additional arcs that model rerouting aircraft of other mission areas.

6. Switch aircraft missions (tailswaps). A *tailswap* occurs when two aircraft exchange missions. In a tailswap, cargo is removed from an aircraft and replaced with higher priority dynamic cargo. The removed cargo becomes dynamic cargo therefore creating an added cargo disruption. For this solution to be practical there must be adequate material handling equipment and personnel at the aerial port where the transloading occurs. Tailswaps can also occur to the detriment of the channel route schedule when channel route missions must provide a working aircraft for a higher priority mission in a different mission area in exchange for an aircraft grounded by maintenance problems. In this case, we consider tailswaps to be an added cargo disruption. But when faced with an added cargo disruption with high priority cargo, the offshore cargo bookie might do a tailswap between two channel route aircraft or with an aircraft flying a lower priority mission of another mission area to ensure that the higher priority cargo is transported. All tailswaps are coordinated with the barrelmaster. While we model the added cargo disruptions caused by tailswaps, we do not model tailswaps as an option for solving problems caused by added cargo disruptions.

7. Request additional organic aircraft. The offshore cargo bookie can ask the barrelmaster if any organic aircraft has become available, which occurs when other mission areas no longer need aircraft. Because the offshore cargo bookie must use channels' operating funds to receive additional organic aircraft, he/she desires to first find solutions that use the current resources of the channel route schedule or fill the residual capacity of aircraft from other mission areas. Even if the offshore cargo bookie needs additional aircraft and organic aircraft are available, the aircraft might not be conveniently positioned in the AMC network to alleviate backlogged cargo at OCONUS aerial ports, punctuated by the fact that most aircraft home bases are CONUS. The offshore cargo bookie can leverage the opportunity of the CONUS cargo bookie requesting additional organic aircraft to alleviate backlogs from CONUS bases, because it can be considered an added aircraft disruption if the request is approved. Our models can create additional arcs to represent the residual capacity of the organic aircraft purchased by the CONUS or offshore cargo bookies. However, we do not model the offshore cargo bookie's decision of which organic aircraft to purchase and how to route those aircraft.

8. Request expansion-buy aircraft. The offshore cargo bookie can work with the commercial scheduler to request expansion-buy aircraft. This is much more expensive relative to requesting additional organic aircraft (partly due to the infrastructure and crew costs not being included in the cost of organic aircraft) and the offshore cargo bookie is directed to make this decision sparingly. The availability of expansion-buy aircraft depends upon the schedules of commercial airlines. We do not model the decision of which expansion-buy aircraft to request.

9. Backlog cargo. Because backlogging cargo decreases customer service, the offshore cargo bookie usually makes this decision as a last resort. Once channel cargo has been backlogged, it will remain at an aerial port until a solution can be found sometime in the future.

The offshore cargo bookie will find a solution as quickly as possible. In our models, an infeasible solution implies backlogging cargo is the only remaining option. When opportunities arise to transport the backlogged cargo, our models will then find a feasible solution.

4.1.4 The Offshore Cargo Bookie Daily Routine

The offshore cargo bookie normally re-plans the channel route schedule at fixed time intervals because every twenty-four hours they find and implement solutions to problems resulting from disruptions within the last twenty-four hours. The offshore cargo bookie's re-plan of the channel route schedule goes into execution usually after he/she finishes coordinating the implementation of the solutions late in the afternoon each day. The offshore cargo bookie re-plans far enough into the future to handle the problems resulting from current added cargo disruptions, which is usually between a few hours and an entire week. *Figure 4-3* shows how the offshore cargo bookie re-plans the channel route schedule at fixed time intervals. Notice that a re-planned schedule is not fully executed before it is re-planned again. As an exception, the offshore cargo bookie re-plans on an event-basis when problems resulting from disruptions need immediate solutions or when contacted by the aircrew, aerial ports, or APCC. Because the offshore cargo bookie is often at home when these problems occur, he/she has limited access to data.

The vision of this thesis is to create models that can be implemented as an offshore cargo bookie decision support tool. A decision support tool could make the biggest impact during the re-planning period of an offshore cargo bookies' day, because the offshore cargo bookie makes most decisions during this time (see §4.1.3). However, our models might also be useful to help

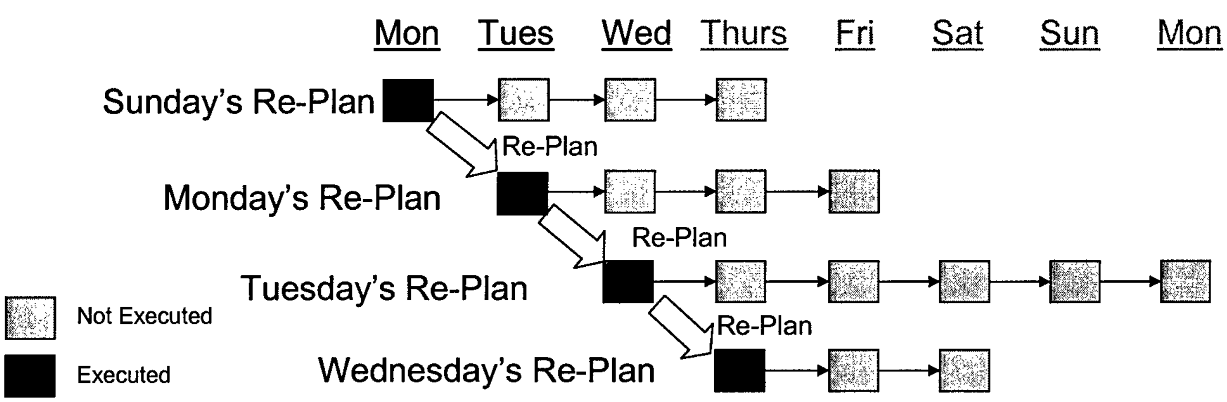

Figure 4-3: Re-plans of the offshore cargo bookie

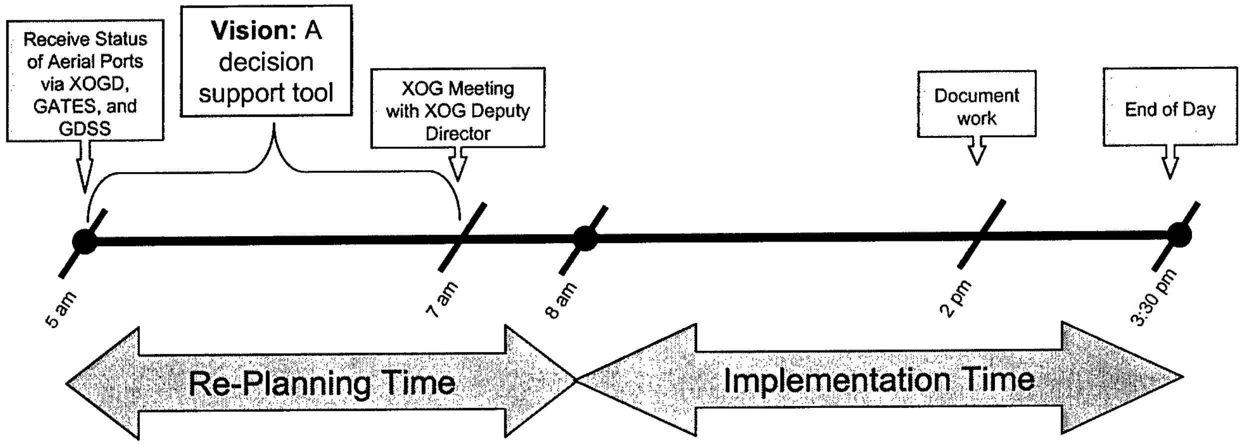

Figure 4-4: Vision of a decision support tool in the daily routine of the offshore cargo bookie

make decisions on an event-basis if the offshore cargo bookie has access to input data required for a decision support tool. *Figure 4-4* shows the vision where such a decision support tool fits in the context of the daily routine of the offshore cargo bookie.

4.2 Modeling the Offshore Cargo Bookie Process

The offshore cargo bookie process is a challenging problem due to the large amount of information available and the number of complex decisions that need to be made. This problem would be ideally solved using a "black box" approach such that a single model can consider all input and then generate an optimal solution (see *Figure 4-5*). This would make sense of the large amounts of information, allowing the offshore cargo bookie to make well-informed decisions.

To make the problem tractable, the method in this thesis decomposes the offshore cargo bookie re-planning period into a sequence of decisions, *Steps 1-8* in *Figure 4-6* (page 76). The decomposition contains three main models. The first model, which we call the *aircraft purchase formulation* (*Step 4*), decides commercial expansion-buy routes, routes of additional acquired organic aircraft, and tailswaps. This formulation remains for future research. Second, the *execution recovery formulation* (*Step 5*) decides how to reroute aircraft of different mission areas in order to alleviate added cargo disruptions. Third, the *MOG compliance formulation* (*Step 6*) strategically delays aircraft to avoid violating MOG limits.

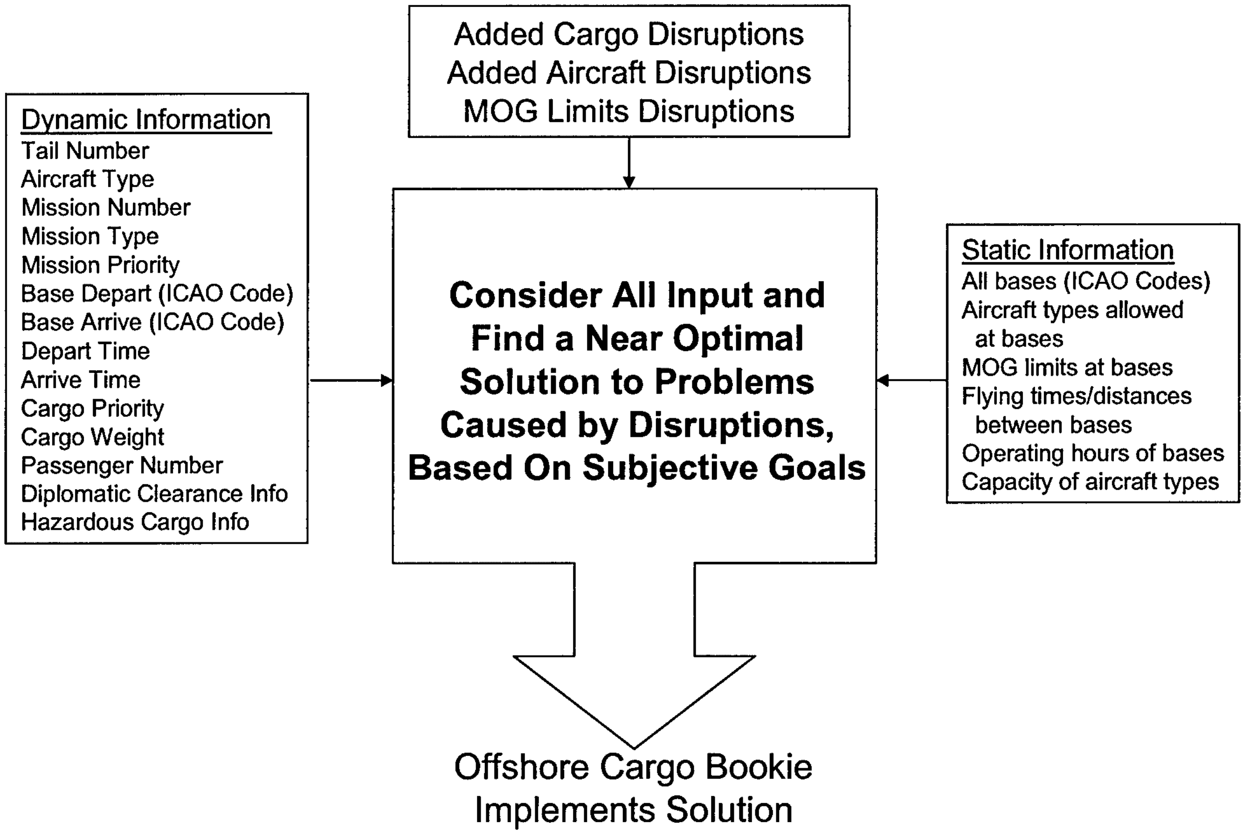

Figure 4-5: The "black box" perspective of solving problems caused by disruptions

The remaining five steps are heuristics. The first heuristic (*Step 1*) models GDSS data as *arc objects*, explained in the next paragraph. This heuristic reroutes and delays aircraft, so they can transport dynamic commodities. The second heuristic (*Step 2*) leverages a rare added aircraft disruption that occurs when all originally scheduled cargo, transported by a single aircraft and originating from or destined to the same aerial port, is cancelled (i.e., the cargo does not enter the AMC network). In this case, the aircraft no longer needs to visit a specific aerial port, so this heuristic will reroute the aircraft to transport dynamic commodities. We do not create this heuristic. The third heuristic (*Step 3*) creates *paths objects*, which are further discussed below, using information from the arc objects. A path object represents a sequence of aircraft flight legs that is a candidate for transporting a dynamic commodity. In other words, this heuristic finds options to transport dynamic commodities using aircraft currently scheduled to be in the AMC network. This heuristic also removes unneeded arc and path objects. If it cannot find transportation for all the dynamic commodities, the arcs and paths are input to the aircraft purchase formulation to select additional aircraft. The fourth heuristic (*Step 7*), which we do not

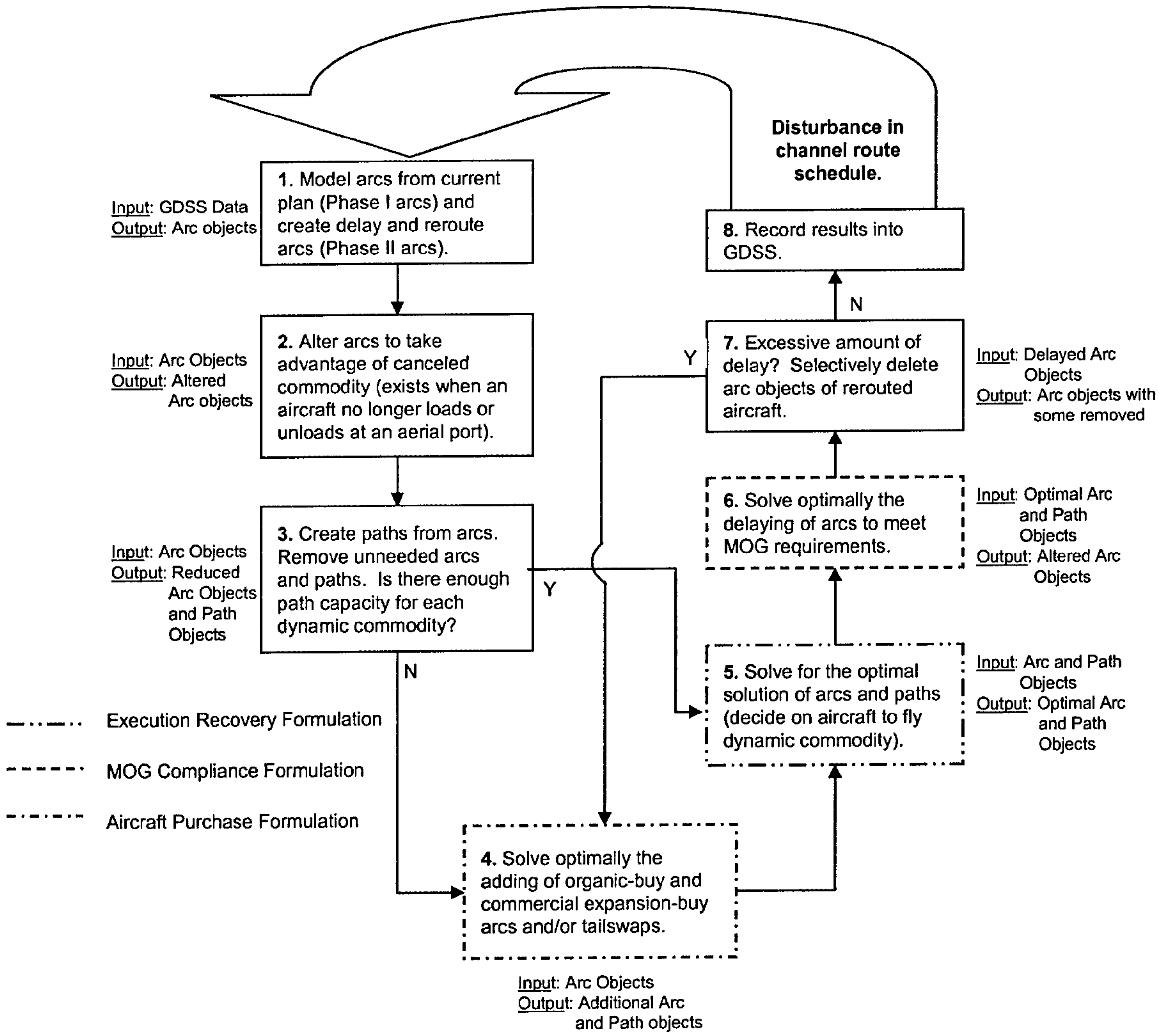

Figure 4-6: A decomposition of the offshore cargo bookie decision-making process

create, selectively removes arc objects of rerouted aircraft, if the MOG compliance formulation excessively delays aircraft. The idea is to disallow rerouting of certain aircraft that add congestion to aerial ports near their MOG limits. Because rerouted aircraft transport dynamic commodities, additional aircraft might be needed to transport the dynamic commodities, which are found using the aircraft purchase formulation. The fifth heuristic (*Step 8*) will transform the arc and path objects into GDSS data.

The unvarying arc object structure stores information needed in all steps. In addition to the information found in the arcs presented in Chapter 3 (i.e., capacity, origin, and destination), the arc objects contain information that is particular to the AMC network, such as DIPS status, HAZMAT status, tailnumber of aircraft, and residual capacity. Similarly, the path objects have an unvarying structure and contain information beyond the paths presented in Chapter 3. Because the arc and path objects serve the same fundamental purpose as the arcs and paths of Chapter 3, we will call them arcs and paths for the remainder of the thesis. The arcs and paths are the input and output of *Steps 2-7*. Because *Step 1* and *Step 8* interface with GDSS, they either have arcs and paths as input or arcs as output.

To bring all steps of the decomposition together, this paragraph presents an overview of the flow of arcs and paths. The arcs begin in *Step 1*, where GDSS data is transformed into arcs. This step also reroutes and delays aircraft so they can fly to the APOEs and APODs of the dynamic commodities. In *Step 2*, the heuristic leverages rare opportunities to transport dynamic commodities, which alters the arcs output from *Step 1*. The arcs from *Step 2* are input to *Step 3* to find paths that can transport the dynamic commodities. If the paths are sufficient to transport all the dynamic commodities, the arcs and paths are output to *Step 5*. If the paths are not sufficient, additional aircraft must be purchased and *Step 4* decides which aircraft to purchase and the routes of those aircraft. *Step 5* selects an optimal subset of the input arcs and paths that transports all the dynamic commodities. This optimal subset of arcs and paths is input into *Step 6*, where some of the arcs are altered, to represent aircraft strategically delayed to adhere to MOG limits. The delayed arcs and the paths are input into *Step 7*. If some of the aircraft are excessively delayed, some of the rerouting in *Step 1* is undone and the altered arcs and paths are re-input into *Step 4* to find additional aircraft to transport the dynamic commodities. Otherwise, the unaltered arcs and the paths are input into *Step 8*, which transforms the arcs and paths into GDSS data.

In the remainder of this section we first describe the execution recovery formulation and the heuristics of creating arcs (*Step 1*) and paths (*Step 3*) of a time-space graph that models the AMC network. Next, we describe the MOG compliance formulation. We finish by describing the concepts behind the aircraft purchase formulation and the heuristics found in *Step 2* and *Step 7*.

4.2.1 The Execution Recovery Formulation

In this section, we introduce the execution recovery formulation (ERF), which is based on the service network design problem formulation (SNDP-F), presented in §3.2. The heuristics used in *Step 2* and *Step 3* leverage AMC operating rules to overcome the disadvantages of the service network design problem formulation, so we use this section to present those heuristics.

These heuristics are called the *arc and path creation heuristics* and the *arc and path reduction heuristics*. We also introduce a time-space graph, which is used as a framework to model the arcs and paths. We find a solution using three methods: multi-mission, diverting aircraft, and transloading cargo. We use a multi-mission approach because it considers aircraft from all mission areas to transport dynamic cargo. Second, we divert aircraft by delaying and rerouting existing aircraft to fly to APOEs and APODs of dynamic cargo. Finally, we allow certain dynamic commodities to be transloaded between aircraft if a single aircraft does not fly between the dynamic commodities' APOEs and APODs.

4.2.1.1 The Time-Space Graph

A time-space graph is used to represent both the physical locations of the aerial ports and time at the aerial ports, where time is partitioned into equal *time periods*. In the ERF, arcs represent aircraft with residual capacity and each aerial port is represented by many nodes, with each node representing a different time period. An arc between two nodes that represent different aerial ports is called a *flight arc*. When an aircraft remains at an aerial port for more than one time period, the aircraft is represented by a *ground arc*, therefore connecting two nodes in sequential time periods of an aerial port. A ground arc also represents the capacity of the aerial port. We define a *path* as a sequence of flight and ground arcs that can transport a fraction of a dynamic commodity, where the second node of an arc in a path is the same as the first node of the next arc in the path. *Figure 4-7* shows a time-space graph with flight and ground arcs.

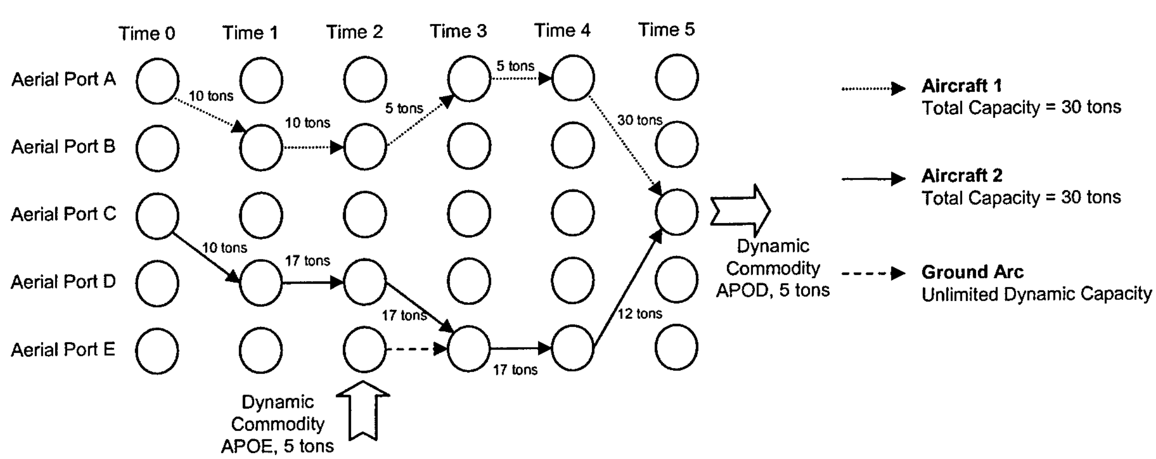

Figure 4-7: An example of the time-space graph

Example 4-2: *Consider Aircraft 1 in Figure 4-7. This aircraft has a total capacity of 30 tons. It is scheduled to fly between aerial port A and aerial port B then back to aerial port A and ending at aerial port C. At aerial port B it is scheduled to unload 20 tons of cargo and then load 25 tons of cargo to be flown to aerial port A. We focus our attention on the residual capacity, which is 10 tons from aerial port A to aerial port B, 5 tons from aerial port B to aerial port A and 30 tons from aerial port A to aerial port C. Now consider aircraft 2 which is scheduled to fly 20 tons of cargo from aerial port C to aerial port D, where it unloads 7 tons of cargo, then flies to aerial port E. At aerial port E the aircraft can potentially be loaded with 5 tons of dynamic commodity. It then flies to aerial port C with a residual capacity of 17 tons. If it does transport the dynamic commodity, the dynamic commodity can be unloaded at aerial port C.*

4.2.1.2 Arc and Path Creation Heuristics and ERF Control Parameters

This section is an overview of the control parameters that are used in the arc and path creation heuristics and the ERF. These control parameters will be referenced in Chapter 5 by their corresponding control parameter number (see *Table 4-1*). The control parameters represent operational constraints or limit the size of the model. The first three control parameters are used to control the size of the time-space network. The C1 and C2 control parameters specify what mission data is retrieved from GDSS by setting times by which each mission must begin and end, so the ERF can remove a portion of the schedule from GDSS that is affected by an added cargo disruption and then re-plan that portion. The C3 control parameter dictates how accurately the model resembles the time continuum of the real world and affects the number of nodes that will be created in the time-space graph. The remaining control parameters are used in the arc and path creation heuristics to limit the possible combinations of arcs and paths. For example, C8 and C9 dictate how early or late dynamic cargo can arrive at its APOD relative to a promised time of arrival. Chapter 5 describes the control parameters in more detail and shows the sensitivity of the model to changes in the control parameters.

Control Parameter	*Explanation*
C0: Begin Time	Aircraft flight legs must depart from their departure aerial ports by this time in order to be modeled.
C1: End Time	Aircraft flight legs must arrive at their arrival aerial port by this time in order to be modeled.
C2: Time Periods per Day	The time fidelity of the model.
C3: Min Dynamic Commodity Split Percent	The smallest percent of a single dynamic commodity that can be loaded onto different aircraft.
C4: Min Aircraft Residual Capacity Percent	The smallest percent of an aircraft's total capacity that must be residual capacity for the aircraft to transport dynamic commodities.
C5: Max Time Periods Rerouted Aircraft Can Wait at New Aerial Port	If an aircraft is rerouted to a new aerial port, this is the maximum time an aircraft can wait for a dynamic commodity's Available to Load Time (ALT).
C6: Max Miles for Rerouted Aircraft to New Aerial Port	The maximum number of miles an aircraft can be rerouted from its scheduled route.
C7: Ground Time Periods for Rerouted Aircraft	How much time a rerouted aircraft must spend at a new aerial port (e.g., time for fueling and cargo loading).
C8: Max Early Time Periods for Dynamic Commodity	The maximum amount of time a dynamic commodity is allowed to wait at its APOD before its promised time.
C9: Max Late Time Periods for Dynamic Commodity	The maximum amount of time a dynamic commodity is allowed to arrive at its APOD after its promised time.
C10: Max Time Periods Rerouted Aircraft can Wait for New Aerial Port Ops Hours	The maximum amount of time a aircraft can wait at an aerial port for the operational hours of another aerial port that the aircraft might be rerouted to.
C11: Max Waiting Time Periods for Dynamic Commodity	How much time a dynamic commodity can wait at its APOE after available to load time (ALT).
C12: Max Number Transloads for Dynamic Commodity	The maximum number of times a dynamic commodity can be transloaded while traveling from its APOD to its APOE.

Table 4-1: List of execution recovery formula (ERF) control parameters

4.2.1.3 Creating Arcs

In the ERF, flight arcs represent a specific aircraft flying between two aerial ports with residual capacity, and ground arcs represent either the residual capacity of an aircraft parked on the ground or the capacity of an aerial port. Arcs are created in two phases; the first phase translates input data from GDSS into flight and ground arcs and the second phase uses heuristics to create diversion arcs by rerouting and delaying aircraft. The two phases are represented as *Step 1* in *Figure 4-6*.

During the first phase, information listed in *Figure 4-8* is retrieved from GDSS. The departure and arrival times of aircraft are converted into time periods and the information is stored in arrays. Because GDSS does not explicitly store ground times, the times of a ground arc are calculated to be the time from when the aircraft arrives at an aerial port until it departs the aerial port. Ground arcs are also created to represent the aerial port cargo capacity, which we assume to be unlimited, as do AMC operators.

Aircraft Tail Numbers (Serial Numbers)
Aircraft Type
Departure Aerial Ports
Arrival Aerial Ports
Departure Times
Arrival Times
Weight of Scheduled Cargo
Priorities of Missions Flown
HAZMAT Information
DIPS Information
Mission Type

Figure 4-8: Input information required for arc creation heuristic

The second phase creates arcs by either: 1) rerouting aircraft from their original routes, which models the offshore cargo bookie's decisions to divert aircraft to utilize residual capacity without acquiring additional aircraft; or 2) creates arcs by delaying aircraft, which models aircraft waiting for dynamic commodities' ALT. If the new route of a rerouted or delayed organic aircraft is in the sequence listing and does not require DIPS, then the offshore cargo bookie coordinates proposed changes with the barrelmaster. Otherwise, the DIPS office is consulted in addition to the barrelmaster. The offshore cargo bookie works with the commercial scheduler to reroute or delay fixed-buy and expansion-buy aircraft. *Example 4-3* illustrates a scenario where the offshore cargo bookie desires to reroute an aircraft.

The second phase accounts for AMC operational rules (e.g., aerial port operating hours and the range of aircraft) and the number of arcs it creates is limited in size by control parameters. *Figure 4-10* shows the algorithm that is used for finding delay and reroute arcs to

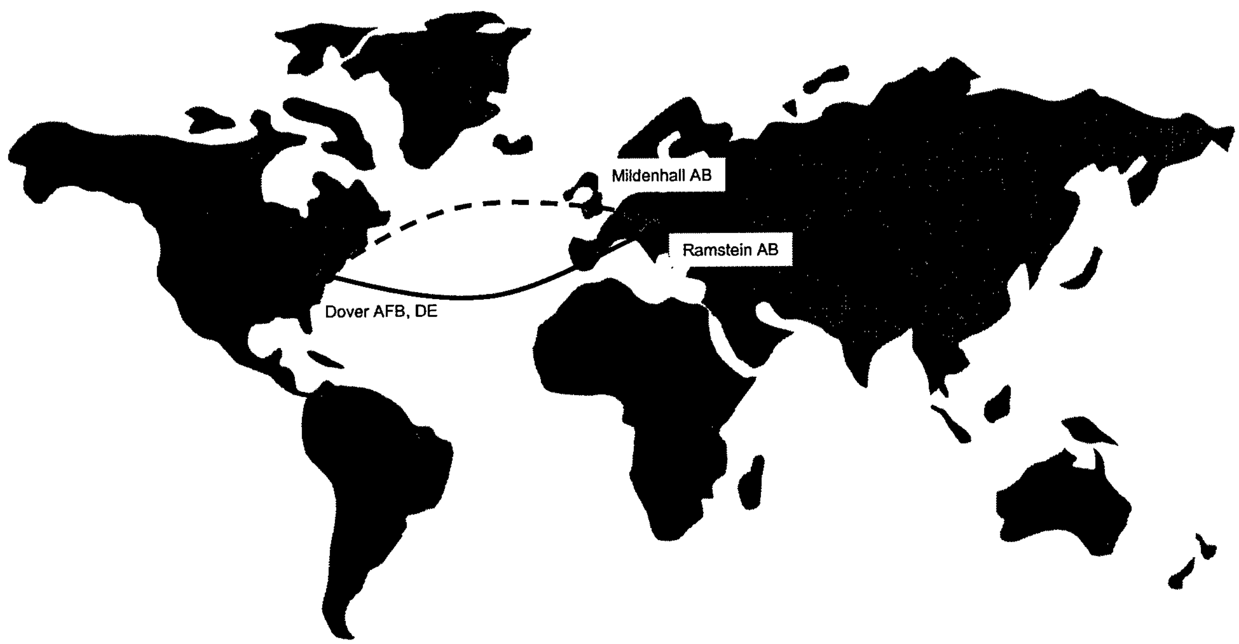

Figure 4-9: An example of an aircraft reroute

> ***Example 4-3:*** *Figure 4-9 shows a C-17 that is scheduled to fly from Dover Air Force Base, Delaware to Ramstein Air Base, Germany with 10,000 lbs of residual capacity. However, Mildenhall Air Base, Great Britain has experienced an added cargo disruption of 5,000 lbs that needs to be transported to Ramstein Air Base. The offshore cargo bookie has the option of rerouting the C-17 from Dover Air Force Base to Mildenhall Air Base to transport the dynamic commodity.*

dynamic commodities' APOEs and APODs. The algorithm searches the flight route of each aircraft to check if the aircraft can be rerouted to an APOE or, if already scheduled to be at an APOE, delayed to wait for a dynamic commodity's ALT. If an aircraft can be rerouted to an APOE, arcs are created that represent the aircraft flying from its original route to the APOE and then flying from the APOE back to its original flight route arcs, which are copied and then altered to represent the aircraft flying behind schedule. If an aircraft can be delayed at an APOE, arcs are created that represent the additional time the aircraft spends at the APOE and the remaining original flight arcs are copied and then altered to represent the aircraft flying behind schedule. In addition, the second phase reroutes aircraft to APODs when searching original aircraft flight routes and searches the new routes that are rerouted to APOEs to see if the aircraft can also be rerouted to APODs. This allows a dynamic commodity to fly on the same aircraft from its APOE to its APOD or allows an aircraft to be rerouted to more than one aerial port. *Example 4-4* gives an overview of the second phase of delaying and rerouting aircraft, where node n represents both an aerial port and a time period, y is a counter that the algorithm iterates at each node in an aircraft's flight route, ALT is the available to load time, and PRS represents the promised time of when the dynamic commodity tentatively arrives at its APOD.

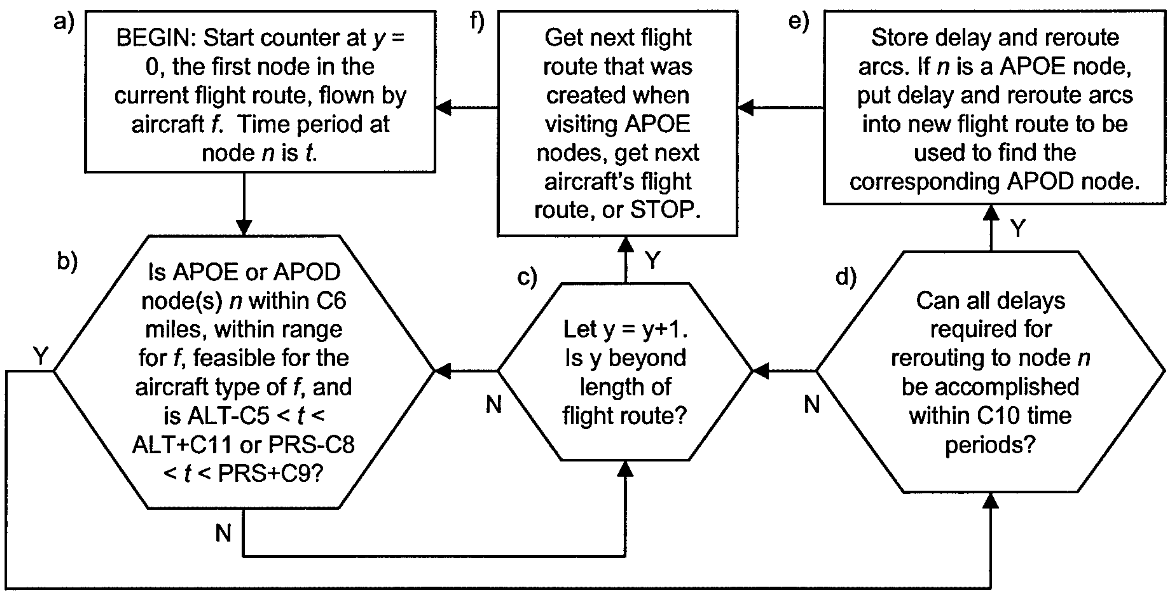

Figure 4-10: The algorithm for the second phase of the arc creation heuristic

Example 4-4: *Consider the aircraft in Figure 4-11a (next page). The aircraft's route consists of the following sequence of nodes: aerial port E at time period 0, aerial port D at time period 1, aerial port C at time period 2 and aerial port E for time periods 3, 4 and 5. The counter y represents the algorithm's current node in the current aircraft route. When the algorithm first starts to process this aircraft route, y = 0 and the algorithm is at aerial port E at time period 0. Now suppose that the aircraft has residual capacity to transport a dynamic commodity from aerial port E with an ALT of time period 1 and promised time of time period 5. Also suppose the dynamic commodity can arrive up to 3 time periods early to its APOD. It is possible to delay the aircraft at aerial port E in order to transport the dynamic commodity. To delay the aircraft, additional arcs are*

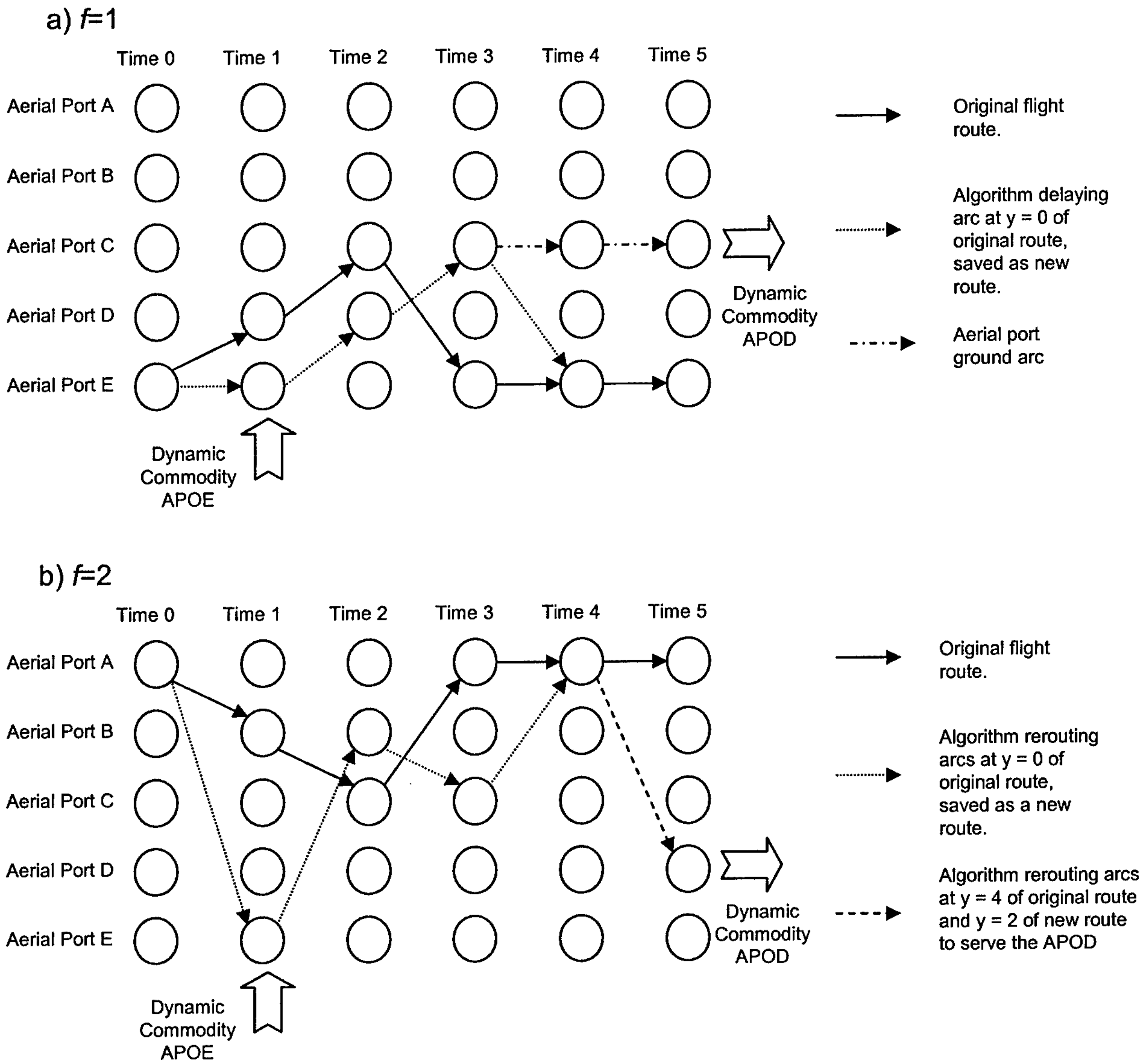

Figure 4-11: Examples of delaying and rerouting aircraft

created to represent the aircraft being delayed on the ground at aerial port E and being behind schedule for the remainder of the route. The resulting arcs are used to create an additional route for the aircraft. Next, the algorithm continues on with the original route: y=1 at aerial port D at time period 1, y = 2 at aerial port C at time period 2, and so on. Because the aircraft visits the dynamic commodity's APOD after the maximum early time and before the promised time on the original route, the algorithm does not need to delay or reroute the aircraft. Now, the algorithm processes the next route of the aircraft, created when the aircraft was rerouted to the APOE. The algorithm follows *through the route to see if the aircraft can be delayed or rerouted to the dynamic commodity's APOD: $y = 0$ at aerial port E at time period 0, $y = 1$ at aerial port E at time period 1, $y = 2$ at aerial port D at time period 2, and so on. Because the aircraft visits the dynamic commodity's APOD after the maximum early time and before the promised time on this route, the algorithm does not need to delay or reroute the aircraft. Because there are no remaining routes, the algorithm stops.*

Now consider the aircraft in Figure 4-11 b. The aircraft will fly the sequence of nodes: aerial port A at time period 0, aerial port B at time period 1, aerial port C at time period 2, and aerial port A at time periods 3, 4, and 5. Now suppose that the aircraft has dynamic cargo capacity to transport dynamic commodity from aerial port E with ALT of 1 and promised time of time period 5. Also suppose that the dynamic commodity cannot arrive early at its APOD and that the aircraft's range is such that it can only fly to aerial port D from aerial port A. The algorithm begins processing the original route: $y = 0$ at aerial port A at time period 0. Because the aircraft can be rerouted to the dynamic commodity's APOE, the algorithm creates two additional arcs: aerial port A at time period 0 to aerial port E at time period 1 and aerial port E at time period 1 to aerial port B at time period 2. Also, the algorithm creates additional arcs representing the aircraft flying the remainder of the original route behind schedule. These additional arcs are used to create an additional route for the aircraft. Next, the algorithm will continue through the original route: $y = 1$ at aerial port B at time period 1, $y = 2$ at aerial port C at time period 2, and so on. When the algorithm reaches $y = 4$ at aerial port A at time period 4, the aircraft can be rerouted to serve the dynamic commodity's APOD (in case the dynamic commodity is transloaded onto this aircraft at one of the previous nodes). Additional arcs are created to represent the aircraft being rerouted to the dynamic commodity's APOD. Once the algorithm has completed the aircraft's original route, it processes the first additional route, created when the aircraft was rerouted to the dynamic commodity's APOE, to search for the dynamic commodity's APOD. The algorithm follows through the additional route, starting after the aircraft is rerouted: $y = 0$ at aerial port B at time period 2 and $y = 1$ at aerial port C at time period 3. When the algorithm reaches $y = 2$ at aerial port A at time period 4, the aircraft can be rerouted to serve the dynamic commodity's APOD to deliver the dynamic commodity, with the additional arcs being saved. Because there are no remaining routes, the algorithm stops.

4.2.1.4 Creating Paths

The paths in the ERF are sequences of arcs that can feasibly transport a specific dynamic commodity from its APOE to its APOD. The paths are created in *Step3* of *Figure 4-6* using a simple recursion algorithm that begins at a dynamic commodity's APOE and then will "worm" through all the arcs, stopping when it either reaches the dynamic commodity's APOD or it violates a path constraint. The path constraints are based upon the control parameters (see §4.2.1.2) and are presented below.

1. **Paths must follow arcs through time.** This constraint forces all arcs to be directional. In the context of the time-space graph, the paths will continuously flow from left to right.

2. **Arcs must have sufficient residual capacity.** This constraint limits the number of paths by ensuring arcs are capable of transporting the minimum percent of dynamic commodity. Because AMC transports commodities by the discrete unit of a pallet, it is valuable to AMC operations that individual pallets are not changed, which can be set by control parameter C3. It is sometimes desirable that a dynamic commodity should fill a certain fraction of the residual capacity for a reroute to be worthwhile, so the minimum fraction of residual capacity can be set by control parameter C4. For example, it is not cost effective to reroute a C-5 aircraft to transport one additional pallet.

3. **Paths must include transloading time for dynamic commodities.** When a path arrives at an aerial port on one aircraft and leaves the aerial port on a different aircraft, it must remain at the aerial port for a minimum number of time periods, set by control parameter C7.

4. **Paths must have a limited number of transloadings.** Transloading uses valuable material handling and personnel resources and requires extra time, so it is desirable to minimize the total number of transloadings on a single path, set by control parameter C12.

5. **Paths must arrive at the APOD before the commodity's maximum late time.** This constraint enhances customer service and limits the number of paths by creating a stopping point in time. The stopping time for paths is the sum of the promised time period and the value of control parameter C9.

6. **Paths cannot visit the same aerial port on two different occasions.** Because the channel route schedule is always changing, this constraint decreases the chance of a dynamic

commodity being delayed by reducing the complexity of the path, and it eliminates the possibility of a dynamic commodity using an aircraft to visit the same aerial port twice.

7. Aerial port ground arcs cannot be between two ground arcs of the same aircraft. This constraint is used to limit the number of path combinations by ensuring that a dynamic commodity will not be unloaded from an aircraft, only to be loaded back onto the same aircraft.

The path constraints derived from AMC's operating rules limit the number of possible paths, illustrating how the structure of the real problem helps control the scope of the mathematical problem. *Example 4-5* shows how paths are created.

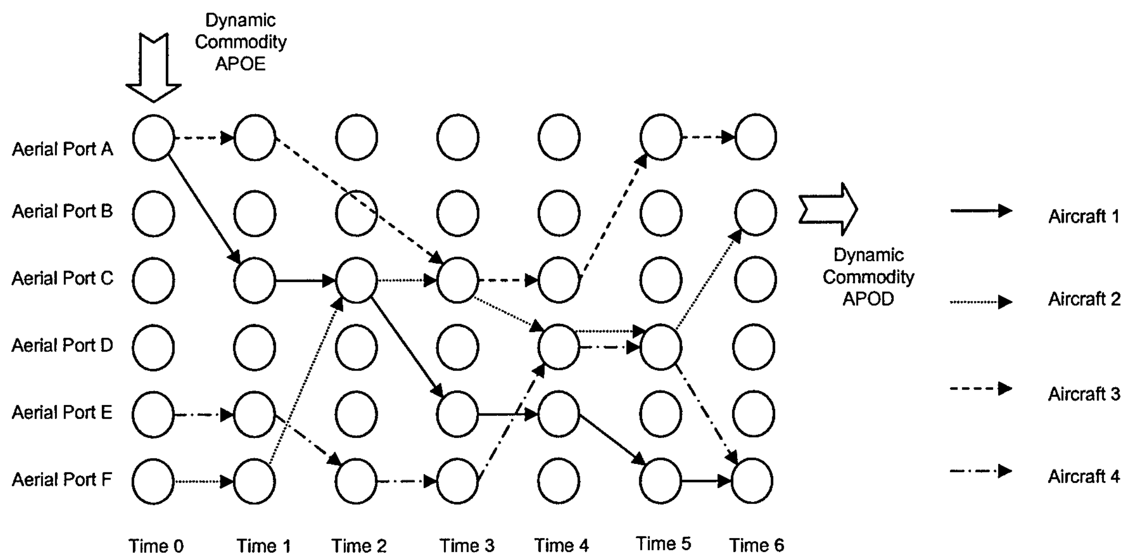

Figure 4-12: Examples of creating paths

Example 4-5: *Consider the arcs in Figure 4-12 for aircraft 1, 2, 3, and 4. Also, consider a dynamic commodity with an ALT at time period 0 and a promised time at time period 6 that needs transportation from aerial port A to aerial port B. Assume that the dynamic commodity can be loaded instantly, but requires one time period for transloading. Also, the dynamic commodity cannot be transloaded more than once, all aircraft have sufficient residual capacity for the dynamic commodity, and the dynamic commodity must be loaded at its APOE and arrive at its APOD exactly on time.*

Now, let's "worm" our first path through the network. First, the dynamic commodity is loaded onto aircraft 3 and arrives at aerial port C. The dynamic commodity cannot be transloaded to aircraft 2 due to insufficient time. So, we go onto *aerial port A. However, at this point it is time period 6 and we are not at aerial port B, so we must stop and the path is not saved.*

For the second path, the dynamic commodity is loaded onto aircraft 1, is transported to aerial port C and is not transloaded to aircraft 2 on this path. Once again, we must stop at aerial port F and not save the path because it has reached time period 6 without getting to aerial port B.

For the third path, the dynamic commodity is once again loaded onto aircraft 1 but on this path it is transloaded to aircraft 2. The dynamic commodity could also be transloaded onto aircraft 3, but this option is not considered because it exceeds the maximum number of transloads. Now, we arrive at aerial port D. Here, we can transload the dynamic commodity to aircraft 4, but this path is not saved, because it exceeds the maximum number of transloads. Then, we continue on to aerial port B. We are now at time period 6 and at the APOD, so we have found a valid path.

In conclusion, there are many potential paths for this simple example, but operating constraints allow only one path to be feasible. Note that if there had been two or more feasible paths, it is possible for each path to transport a fraction of the dynamic commodity.

4.2.1.5 Arc and Path Reduction Heuristics

Once the arcs and paths are created, as presented in the last two sections, it is possible to discard many of the saved arcs and paths by using additional heuristics, therefore decreasing the size of the ERF. In our arc and path reduction heuristics, each situation listed below is based on information of both the arcs and paths, leveraged to reduce the number of arcs and paths.

A. Aircraft does not contribute as a resource. If an aircraft is not used in any path, there is no reason to include its arcs in the model because it does not contribute as a resource. This situation is used to discard a large portion of the arcs.

B. Commodity flows through many different combinations of ground arcs while at a single aerial port. In this situation, many combinations of paths arise when a dynamic commodity is on the ground at an aerial port with many aircraft ground arcs, because there are many ways it can transload among the aircraft. For example, a dynamic commodity could flow through an aerial port ground arc one time period, then flow through an aircraft ground arc the second time period, then flow through a different aircraft ground arc the third time period and so on. To remove all these combinations, we discard paths that have a dynamic commodity flowing through other than aerial port ground arcs or the aircraft ground arcs of the aircraft that will transport the commodity away from the aerial port.

C. **Arcs are not used in paths.** When an arc is not used in any path, then it does not contribute as a resource and can be discarded. However, this must be done carefully, because the aircraft resource might need to fly along the arcs associated with the original schedule if the ERF decides not to use the aircraft in paths that use the aircraft's rerouted arcs, so the arcs associated with the original schedule must be preserved while the arcs created using heuristics that are not used in any path can be discarded.

4.2.1.6 ERF Integer Program Details

This section will present the core of the ERF, based upon the service network design problem formulation (see §3.2). All notation required to present the ERF will be shown in this section. A crucial difference between ERF and the service network design problem formulation is that ERF does not aggregate aircraft flying between two locations into a single arc. While this might cause the model to be more complex by increasing the number of arcs, it allows ERF to schedule dynamic commodity to specific aircraft. Note that the network structure in ERF includes only the arcs and paths that remain after the arc and path reduction heuristics presented in the previous section. ERF finds an optimal subset of this set of reduced arcs and paths.

Aerial Ports, Aircraft and Dynamic Cargo

N set of all nodes $i \in N$ in the time-space graph;

F set of all aircraft $f \in F$, differentiated by unique tail numbers;

K set of all dynamic commodities $k \in K$;

Network Structure

A set of all arcs $(i, j) \in A$ in the time-space graph, where $i, j \in N$;

P set of all paths $p \in P$ in the time-space graph;

A^f set of all arcs $(i,j) \in A^f$ for aircraft $f \in F$, where $i, j \in N$, $A^f \subseteq A$, $\bigcup_{f \in F} A^f = A$ and $A^f \bigcap A^r = \varnothing$ $\forall f, r \in F$ such that $f \neq r$;

L^f set of flight arcs $(i,j) \in L^f$ for aircraft $f \in F$, where $i, j \in N$ and $L^f \subseteq A^f$;

P^k set of all paths $p \in P^k$ for dynamic commodity $k \in K$, where $P^k \subseteq P$;

Data

u_{ij}^f residual capacity of aircraft $f \in F$ on arc $(i,j) \in A^f$;

d_{ij}^f cost of flying aircraft $f \in F$ on arc $(i,j) \in A^f$;

c_p^k cost of transporting commodity $k \in K$ on path $p \in P^k$;

s smallest fraction of a dynamic commodity that can be split into to be transported on different paths;

b^k the weight of dynamic commodity $k \in K$ ($b^k > 0$);

$$\delta_{ij}^p = \begin{cases} 1, \text{ if arc } (i,j) \in A \text{ is included in path } p \in P \\ 0, \text{ otherwise;} \end{cases}$$

Decision Variables

$$y_{ij}^f = \begin{cases} 1, \text{ if aircraft } f \in F \text{ will fly along flight arc } (i,j) \in A^f \\ 0, \text{ otherwise;} \end{cases}$$

$$z_p^k = \begin{cases} 1, \text{ if dynamic commodity } k \in K \text{ will be transported on path } p \in P^k \\ 0, \text{ otherwise;} \end{cases}$$

x_p^k the fraction of dynamic commodity $k \in K$ transported on $p \in P^k$;

$$\text{ERF} = \quad min \sum_{k\in K}\sum_{p\in P^k} c_p^k x_p^k + \sum_{f\in F}\sum_{(i,j)\in A^f} d_{ij}^f y_{ij}^f \tag{4.1}$$

s.t.

$$\sum_{k\in K}\sum_{p\in P^k} \delta_{ij}^p b^k x_p^k \le u_{ij}^f y_{ij}^f \qquad \forall f\in F, \forall (i,j)\in L^f, \tag{4.2}$$

$$\sum_{p\in P^k} x_p^k = 1 \qquad \forall k\in K, \tag{4.3}$$

$$x_p^k - z_p^k s \ge 0 \qquad \forall k\in K, p\in P^k, \tag{4.4}$$

$$-x_p^k + z_p^k \ge 0 \qquad \forall k\in K, p\in P^k, \tag{4.5}$$

$$\sum_{\{j:(i,j)\in A^f\}} y_{ij}^f - \sum_{\{j:(j,i)\in A^f\}} y_{ji}^f = 0 \qquad \forall i\in N, f\in F, \tag{4.6}$$

$$y_{ij}^f \in \{0,1\} \qquad \forall f\in F, \forall (i,j)\in A^f, \tag{4.7}$$

$$x_p^k \ge 0 \qquad \forall k\in K, p\in P^k, \tag{4.8}$$

$$z_p^k \in \{0,1\} \qquad \forall k\in K, p\in P^k. \tag{4.9}$$

The objective function (4.1) minimizes the cost of the paths chosen for each commodity and the costs of flying aircraft along specific arcs. Forcing constraints (4.2) ensure the total amount of commodity transported along a specific arc is less than the arc's residual capacity. The convexity constraints (4.3) ensure that the entirety of a commodity is transported. Constraints (4.4) and (4.5) ensure that cargo is not split up below a certain fraction, which represents pallet size considerations. The balance of aircraft flow constraints (4.6) conserve the resource flow at individual bases. We enforce the resource decision variables to be binary (4.7), the fractional commodity path decision variable to be non-negative (4.8), and the cargo split indicator decision variables to be binary (4.9).

Because the execution of the channel route schedule requires the offshore cargo bookie to focus on individual aircraft, we do not aggregate aircraft that fly between the same nodes, as done in the SNDP-F. This requires more arcs, but by limiting the number of paths (see §4.2.1.4), the problem size can solved in a practical amount of time.

4.2.1.7 Subjectively Weighting Arcs and Paths

The decisions of the offshore cargo bookie are subjective, motivating a need to subjectively decide the cost of including specific arcs and paths in the ERF solution. Two types of equations are presented in this section that calculate the subjective costs of arcs and paths, using subjective parameters α, β, γ, ε, ω, λ, ξ, and ζ, which weight individual attributes of the

AMC network. The d_{ij}^f cost variable is the same variable that was presented in the ERF and represents the cost for aircraft $f \in F$ to fly along arc $(i,j) \in A^f$. Similarly, the c_p^k cost variable is the same in the ERF and represents the cost of path p to be used to transport commodity k. The offshore cargo bookie desires to minimize the amount of disruption to the original schedule when rerouting and delaying aircraft to transport dynamic commodities. The subjective weighting can be used to minimize the severity of the disruptions. This section will briefly explain the importance of each of the AMC network attributes in subjectively minimizing disruptions.

In the following mathematical models, we expand on our previous terminology. We consider a flight arc to be *rerouted* if it represents a flight arc in the rerouted portion of a rerouted route of an aircraft (see §4.2.1.3). As an example, suppose a portion of the original route of an aircraft is from aerial port A to aerial port C. This flight arc is the *original* flight arc. Now suppose that the aircraft is rerouted from aerial port A to aerial port B, and then to aerial port C. The flight arcs from aerial port A to aerial port B and aerial port B to aerial port C are rerouted. We also consider a flight arc to be *delayed* if it represents a leg in the delayed portion of a delayed route of an aircraft (see §4.2.1.3). All flight arcs in a rerouted route beyond the rerouted flight arcs are considered to be delayed. Note that ground arcs have zero cost.

<u>AMC Network Attributes</u>

$$DIST_{ij}^f = \begin{cases} \text{the distance of rerouted flight arc } (i,j) \in A^f \text{ minus the distance} \\ \qquad \text{of the original flight arc, if arc } (i,j) \in A^f \text{ is rerouted} \\ 0, \text{ otherwise;} \end{cases}$$

$$DIPS_{ij}^f = \begin{cases} 1, \text{ if aircraft } f \in F \text{ has a route containing flight arc } (i,j) \in A^f, \\ \qquad \text{which is or is before a flight arc requiring DIPS,} \\ \qquad \text{and flight arc } (i,j) \in A^f \text{ is a reouted or delayed flight arc} \\ 0, \text{ otherwise;} \end{cases}$$

$$HAZ_{ij}^{f} = \begin{cases} 1, \text{ if aircraft } f \in F \text{ has a route containing flight arc } (i,j) \in A^f, \\ \qquad \text{which is or is before a flight arc transporting HAZMAT,} \\ \qquad \text{and flight arc } (i,j) \in A^f \text{ is a rerouted or delayed flight arc} \\ 0, \text{ otherwise;} \end{cases}$$

$$PRTY_{ij}^{f} = \begin{cases} 1, \text{ if the highest priority of delayed or rerouted flight arc } (i,j) \in A^f \\ \qquad \text{and all flight arcs after flight arc } (i,j) \in A^f \text{ in a route of} \\ \qquad \text{aircraft } f \in F \text{ containing flight arc } (i,j) \in A^f \text{ is 1A1} \\ 2, \text{ if the highest priority of delayed or rerouted flight arc } (i,j) \in A^f \\ \qquad \text{and all flight arcs after flight arc } (i,j) \in A^f \text{ in a route of} \\ \qquad \text{aircraft } f \in F \text{ containing flight arc } (i,j) \in A^f \text{ is 1A2} \\ \vdots \\ 23, \text{ if the highest priority of delayed or rerouted flight arc } (i,j) \in A^f \\ \qquad \text{and all flight arcs after flight arc } (i,j) \in A^f \text{ in a route of} \\ \qquad \text{aircraft } f \in F \text{ containing flight arc } (i,j) \in A^f \text{ is 4B3;} \end{cases}$$

$$TIME_{ij}^{f} = \begin{cases} 0, \text{ if departure node } n \in N \text{ of flight arc } (i,j) \in A^f \text{ is 0 time periods beyond} \\ \qquad \text{the begin time (control parameter C0) and flight arc } (i,j) \in A^f \\ \qquad \text{is delayed or rerouted} \\ 1, \text{ if departure node } n \in N \text{ of flight arc } (i,j) \in A^f \text{ is 1 time period beyond} \\ \qquad \text{the begin time (control parameter C0) and flight arc } (i,j) \in A^f \\ \qquad \text{is delayed or rerouted} \\ \vdots \\ \text{t-1}, \text{ if departure node } n \in N \text{ of flight arc } (i,j) \in A^f \text{ is t-1 time periods beyond} \\ \qquad \text{the begin time (control parameter C0) and flight arc } (i,j) \in A^f \\ \qquad \text{is delayed or rerouted;} \end{cases}$$

$TARDY_p^k =$ time periods beyond the promised time of dynamic commodity $k \in K$ arriving at its APOD if transported by path $p \in P^k$;

$PLNCHG_p^k$ = the number of transloads required to transport dynamic commodity k on path $p \in P^k$;

$$PRTY^k = \begin{cases} 1, \text{ if priority of dynamic commodity } k \in K \text{ is 1A1} \\ 2, \text{ if priority of dynamic commodity } k \in K \text{ is 1A2} \\ \vdots \\ 23, \text{ if priority of dynamic commodity } k \in K \text{ is 4B3;} \end{cases}$$

β, γ, ε, α, and ω subjective parameters for finding arc costs;

λ, ξ, and, ζ subjective parameters for finding path costs.

Subjective Arc and Path Costs Equations

$$d_{ij}^f = \beta * DIPS_{ij}^f + \gamma * HAZ_{ij}^f + \varepsilon / PRTY_{ij}^f + \alpha * DIST_{ij}^f + \omega / (TIME_{ij}^f + 1) \tag{4.10}$$

$$c_p^k = \frac{\lambda * TARDY_p^k + \xi * PLNCHG_p^k}{\zeta * PRTY^k} \tag{4.11}$$

When the offshore cargo bookie makes decisions, he/she must balance the desire of quickly transporting dynamic commodity with the amount of disruptions that will be imposed on the AMC network. Similarly, there are tradeoffs between the AMC network attributes. For instance, if an aircraft requires DIPS, it might be better to keep that aircraft on schedule and disrupt an aircraft that has a higher priority mission but does not require DIPS. We will now outline the AMC network attributes presented in the mathematical models of this section and how they are affected by disruptions in the schedule.

The Rerouting Distance: When an aircraft is rerouted, it is desirable to minimize the rerouting distance. To capture this fact, the subjective arc cost equation accounts for the additional distance that an aircraft is rerouted. If an arc only delays the original schedule, the aircraft of that arc flies the original distance (i.e., $DIST_{ij}^f = 0$), albeit late.

DIPS: If the flight arcs beyond a rerouted or delayed arc in an aircraft's route require DIPS, then the DIPS might need to be changed to account for a change in time, weight, HAZMAT or flight route. Therefore, it is desirable not to change aircraft routes that need DIPS.

HAZMAT: When an aircraft is rerouted to transport HAZMAT, specialized crew and material handling equipment might be needed at the aerial ports that rerouted arcs visit. This is in addition to the effects it will have on DIPS.

Priority: The priority of an aircraft mission is important in deciding its sensitivity to disruptions. Although commodities are designated with the cargo priority system when validated by USTRANSCOM, the dynamic commodities are usually part of an existing mission, so we designate the priority of these commodities with their mission priority rather than by the cargo priority.

Time: In the execution of missions, personnel are sensitive to how much time they have to prepare for changes (e.g., aircrew needs time to plan for new flight legs), so we use a time parameter that makes changes occurring earlier more costly than the same changes occurring later. In addition, a dynamic commodity arriving late decreases customer service, so the time a commodity arrives late at its APOD has a cost.

Transloadings: Although the creation of the path heuristic can enforce a limit in the number of transloadings, we use the path costs to make more transloadings below the limit more costly than less transloadings below the limit.

4.2.2 The MOG Compliance Formulation (MCF)

Currently, the offshore cargo bookie does not know how his/her decisions affect MOG levels at aerial ports. Rather, the offshore cargo bookie makes changes to the channel route schedule, then the MOG master will react to resulting MOG violations. The MCF can be used to give the offshore cargo bookie feedback on how changes to the schedule affect the MOG levels, and therefore, allow changes to be made that minimize disruptions to the AMC network and minimize excessive delays to channel route missions. This section will present the control parameters used in the MCF and describe the details of the MCF integer program.

Control Parameter	Explanation
L0: Begin Time	Aircraft flight legs must depart from their departure aerial ports by this time in order to be modeled.
L1: End Time	Aircraft flight legs must arrive at their arrival aerial port by this time in order to be modeled.
L2: Time Periods per Day	The time fidelity of the model.
L3: Max Delay Time	The maximum time periods that an aircraft can be delayed on the ground.

Table 4-2: List of MCF control parameters

4.2.2.1 MCF Control Parameters

The MCF control parameters can be used to change the scope of the MCF. Similar to the ERF, the MCF has control parameters that decide the beginning and ending times of the input GDSS data and the time periods per day. Unique to the MCF is the maximum delay for an aircraft (see *Table 4-2, control parameter L3*), which limits the total number of time periods that an aircraft can be grounded at aerial ports beyond its scheduled departure time.

4.2.2.2 The MCF Integer Program Details

MCF is based on the Multi-Airport Ground-Holding Problem Formulation (MAGHP-F), as presented in §3.3. While the MAGHP-F strategically delays aircraft on the ground to avoid congestion when leaving or arriving at airports, AMC wants to ensure that at any given time aerial port MOG limits are not violated. To accomplish this goal, MCF strategically delays certain aircraft in the entire AMC network so that the total cost of delaying aircraft is minimized. Similar to the ERF, the total delay costs are derived from AMC network attributes and subjective parameters.

MCF is not as strongly based on the time-space graph as the ERF, because MCF decouples aerial ports and time periods. While the ERF selects from input arcs that remain unchanged, MCF alters ground arcs by allowing them to grow. For example, consider a ground arc that represents an aircraft being at an aerial port from time period 1 to time period 4. MCF could delay the aircraft by altering the ground arc to represent the aircraft being at the aerial port from time period 1 to time period 6. In addition, MCF implies flight arcs as being the time between a ground arc ending and the next ground arc beginning. The times aircraft spend flying on the flight arcs remain constant, although the departure and arrival times can change as the ground arcs grow. While the ERF and MCF use arcs in different ways, the output of one can be easily translated to be the input of the other. Also note that MCF does not use paths.

Data

E	set of all aerial ports $e \in E$;
G	set of all ground arcs $g \in G$;
G^e	set of ground arcs $g \in G^e$ associated with aerial port $e \in E$;
H	set of all flight arcs $h \in H$;
h_g	the flight arc directly after ground arc $g \in G$;
d_g	scheduled departure time period of the aircraft associated with ground arc $g \in G$;
o_g	number of time periods spent on the ground for the aircraft associated with ground arc $g \in G$;
l_g	number of time periods between ground arc $g \in G$ and the next consecutive ground arc $g' \in G$ for the aircraft associated with ground arc $g \in G$. In other words, it is the flight time of the aircraft associated with flight arc $h_g \in H$;
$M_e(t)$	the MOG limit of aerial port $e \in E$ at time period $t \in T^e$. This represents the most limiting MOG at aerial port $e \in E$ of all MOGs (e.g., PMOG and WMOG);
m_g	the contribution of the aircraft associated with ground arc $g \in G$ towards the MOG limit;
c_g	the marginal cost of delaying the aircraft associated with ground arc $g \in G$;
T_g^a	set of time periods that determine when ground arc $g \in G$ can begin (aircraft arrival time);

T_g^d set of time periods that determine when ground arc $g \in G$ can end (aircraft departure time). T_g^d includes d_g and the remaining elements are consecutive time periods beyond d_g. There is a difference of o_g time periods between corresponding elements of T_g^a and T_g^d;

Decision Variables

$$w_{g,t}^a = \begin{cases} 1, \text{ if the aircraft associated with ground arc } g \in G \text{ arrives by time period } t \in T_g^a \\ 0, \text{ otherwise;} \end{cases}$$

$$w_{g,t}^d = \begin{cases} 1, \text{ if the aircraft associated with ground arc } g \in G \text{ departs by time period } t \in T_g^d \\ 0, \text{ otherwise;} \end{cases}$$

$$\text{MCF} = \quad min \sum_{g \in G} \left[c_g \sum_{t \in T_g^d} (t - d_g)(w_{g,t}^d - w_{g,t-1}^d) \right] \tag{4.12}$$

s.t.

$$\sum_{g \in G^e : t \in T_g^a, t \notin T_g^d} m_g w_{g,t}^a + \sum_{g \in G^e : t \in T_g^a, t \in T_g^d} m_g (w_{g,t}^a - w_{g,t}^d) + \sum_{g \in G^e : t \notin T_g^a, t \in T_g^d} m_g (1 - w_{g,t}^d) \le M_e(t) \quad \forall e \in E, \tag{4.13}$$

$$w_{g,t+o_g}^d - w_{g,t}^a \le 0 \quad g \in G, t \in T_g^a, \tag{4.14}$$

$$w_{g',t+l_g}^a - w_{g,t}^d = 0 \quad \forall g, g' \in G, t \in T_g^d, \tag{4.15}$$

$$w_{g,t}^a - w_{g,t-1}^a \ge 0 \quad \forall g \in G, t \in T_g^a, \tag{4.16}$$

$$w_{g,t}^d - w_{g,t-1}^d \ge 0 \quad \forall g \in G, t \in T_g^d, \tag{4.17}$$

$$w_{g,t}^a \in \{0,1\} \quad \forall g \in G, t \in T_g^a, \tag{4.18}$$

$$w_{g,t}^d \in \{0,1\} \quad \forall g \in G, t \in T_g^d. \tag{4.19}$$

The objective function (4.12) minimizes the cost due to ground delays. Constraints (4.13) ensure that the MOG limitations are met at each aerial port for every time period that pertains to the aerial port. Constraints (4.14) are connecting constraints within ground arcs.

They ensure that ground arcs require no less time than the corresponding ground time presented in the data. Constraints (4.15) are connecting constraints within flight arcs. They ensure that flight arcs require exactly the same number of time periods as the corresponding flight time presented in the data. Constraints (4.16) and (4.17) are connecting constraints of time. For instance, if an arc has arrived at its arrival aerial port by time period t, then the arc has also arrived at its arrival aerial port by time period t+1, t+2, and so on. Finally, constraints (4.18) and (4.19) ensure that the decision variables are binary.

Similar to the subjective equations of the ERF, the delay costs, c_g, in MCF are calculated using subjective parameters β, γ, ε, and ω to weight AMC network attributes. However, the ERF's flight arc costs are based on the flight arcs being included in the model, while the MCF costs are based on the number of time periods aircraft are delayed on the ground. Although the delay costs are for ground arcs, they are based on subsequent flight arcs. The AMC network attributes needed for the MCF cost equations are included below followed by the delay cost per time period equation.

<u>AMC Network Attributes</u>

$$DIPS_g = \begin{cases} 1, \text{ if the flight arc } h_g \in H \text{ is or is before another flight arc requiring} \\ \qquad \text{DIPS in the route of the associated aircraft} \\ 0, \text{ otherwise;} \end{cases}$$

$$PRTY_g = \begin{cases} 1, \text{ if the highest priority of flight arc } h_g \in H \text{ and all flight arcs after} \\ \qquad \text{flight arc } h_g \in H \text{ in the route of the associated aircraft is 1A1} \\ 2, \text{ if the highest priority of flight arc } h_g \in H \text{ and all flight arcs after} \\ \qquad \text{flight arc } h_g \in H \text{ in the route of the associated aircraft is 1A2} \\ \vdots \\ 23, \text{ if the highest priority of flight arc } h_g \in H \text{ and all flight arcs after} \\ \qquad \text{flight arc } h_g \in H \text{ in the route of the associated aircraft is 4B3;} \end{cases}$$

$$TIME_g = \begin{cases} \text{0, if the associated aircraft of ground arc } g \in G \text{ departs the associated aerial} \\ \qquad \text{port 0 time periods beyond the begin time (\textit{control parameter L0})} \\ \text{1, if the associated aircraft of ground arc } g \in G \text{ departs the associated aerial} \\ \qquad \text{port 1 time period beyond the begin time (\textit{control parameter L0})} \\ \vdots \\ \text{t, if the associated aircraft of ground arc } g \in G \text{ departs the associated aerial} \\ \qquad \text{port t time periods beyond the begin time (\textit{control parameter L0});} \end{cases}$$

$$HAZ_g = \begin{cases} \text{1, if the flight arc } h_g \in H \text{ is or is before another flight arc transporting} \\ \qquad \text{HAZMAT in the route of the associated aircraft} \\ \text{0, otherwise;} \end{cases}$$

β, γ, ε, and ω subjective parameters for finding delay costs.

Subjective Delay Cost per Time Period Equation

$$c_g = \beta * DIPS_g + \varepsilon / PRTY_g + \omega /(TIME_g + 1) + \gamma * HAZ_g \tag{4.20}$$

4.2.3 The Aircraft Purchase Formulation and Other Heuristics

The aircraft purchase formulation (APF) accounts for the possibility of the offshore cargo bookie acquiring additional organic aircraft, purchasing commercial expansion-buy aircraft, and scheduling tailswaps. The APF is needed when the ERF is infeasible, meaning that there is not enough capacity on the paths to transport all the dynamic commodities (see §7.2 for future research).

However, there are two methods for the offshore cargo bookie to use the ERF without the APF when the ERF is infeasible. First, he/she could select dynamic commodities to backlog, and then check if the ERF can find a feasible solution. This could be done quickly, because no new arcs or paths would have to be found. Rather, the paths representing backlogged dynamic commodities could be temporarily removed from the ERF. Once a feasible solution is found using the remaining paths, the offshore cargo bookie could find solutions to the backlogged dynamic commodities by manually purchasing additional aircraft and planning tailswaps. Second, the offshore cargo bookie can alter the control parameters to find a feasible solution to the ERF by allowing for more arc and path possibilities. However, this might drastically increase the size of the model and will be explored in Chapter 5.

In *Step 2* of *Figure 4-6*, additional arcs can be heuristically created to help the offshore cargo bookie leverage canceled cargo, where an aircraft no longer loads or unloads cargo at a specific aerial port. Because canceled cargo is rare, the offshore cargo bookie might not be well-prepared to take full advantage of these opportunities. The aircraft scheduled to fly the canceled cargo can be rerouted to transport dynamic commodity and the resulting arcs can be included in ERF. The heuristics used to reroute the aircraft might be similar to the phase two arc creation heuristics, except that there is no motivation to adhere to the original route. So a good reroute might not be to simply search for the closest APOEs and APODs, as done in the phase two arc creation heuristics, but rather, drastically deviate from the original schedule.

In *Step 7*, heuristics can be used to delete arcs of rerouted aircraft that are causing excessive delays due to MOG limits. This causes the solution found by the ERF to be inadequate. Because some of the routes found by the ERF are removed, some dynamic commodities and originally scheduled cargo no longer have transportation. In addition to the dynamic commodities no longer having transportation, the originally scheduled cargo, which became unassigned, causes an additional added cargo disruption. To alleviate this additional added cargo disruption, the APF can be used to find additional aircraft, and then the ERF can reselect an optimal subset of the routes and paths.

4.3 Summary

In this chapter we analyzed the operations of AMC that pertain to the offshore cargo bookie and presented models that could be used towards an offshore cargo bookie decision support tool. To analyze operations, we investigated the general decision guidelines used by the offshore cargo bookie and suggested methods that could be used to incorporate the decisions into the models presented in Chapter 3. We then decomposed the offshore cargo bookie decision process and introduced the ERF and MCF models. We briefly discussed the APF and the heuristics as a whole. In Chapter 5, we present results from the models presented in this chapter on a variety of test cases.

5 Results and Analysis

In Chapter 4, we analyzed the offshore cargo bookie problem and decomposed the overall decision process. We presented ERF, MCF, and arc and path creation heuristics that can be combined to help the offshore cargo bookie find and analyze alternate solutions to disruptions in the channel route schedule. At two hours, the solution time available for the offshore cargo bookie is short, while the amount of information available is large. The current process allows neither time nor tools for "what-if" analysis. In most cases, the offshore cargo bookie only has time to find one solution, and he/she does not know if better solutions exist. The results presented in this chapter illustrate the ability of the models in Chapter 4 to help the offshore cargo bookie find a variety of good solutions.

We divide the chapter into ERF and MCF sections, presenting the arc and path creation heuristics in the ERF section. In the ERF section, we analyze: the effects of changing values of control parameters, the effects of changing values of subjective parameters, the effects of using different data sets, the model's computational performance and the increase in computational complexity that results from additional dynamic commodities. In the MCF section, we analyze the computational performance and the effects of changing the values of both control and subjective parameters. In both sections, we use November 2002 and March 2003 GDSS data sets. The two data sets have been preprocessed using PERL to synthesize cargo loading information and to rectify input errors. All computer code is written in Java using the JBuilder Personal 9 compiler.

5.1 Execution Recovery Formulation Results

ERF finds an optimal subset of arcs and paths that solves problems caused by disruptions in the channel route schedule. While changes can be made to the arc and path creation heuristics, ERF remains the same, making it a flexible approach that can adapt to evolving AMC policies. When ERF is infeasible, there is not enough aircraft capacity to transport all of the dynamic commodities. This is a powerful indicator for the offshore cargo bookie because he/she can confidently begin requesting organic and expansion-buy aircraft or tailswapping missions, potentially aided by the APF (see §4.2.3).

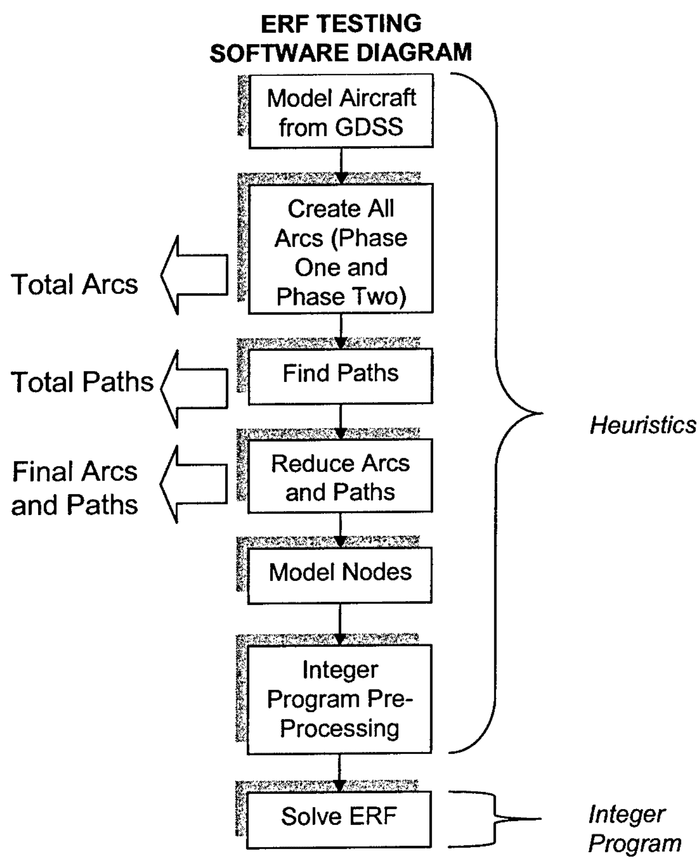

Figure 5-1: ERF testing software diagram

The algorithmic steps used to setup and solve ERF are shown in *Figure 5-1.* The first step takes GDSS data and creates an array of the different types of aircraft. Ground arcs are also considered to be an "aircraft" type to model the capacity of the aerial ports. The next step transforms GDSS data into arcs and then creates additional arcs that model changes and delays in aircraft routes. The resulting arcs are called *total arcs*. The third step finds paths from all the arcs. The resulting paths are called *total paths*. Information from both the total arcs and total paths can be used to remove many arcs and paths (see §4.2.1.5), and the remaining arcs and paths are called *final arcs* and *final paths.* The next step creates network nodes using information from the final arcs and final paths. The ERF constraint rows and objective function are created in the next step. In the final step, the ERF finds the subset of the final arcs and final paths that minimizes total cost, by solving the integer program (IP) using XPress-MP 2003 software.

5.1.1 ERF Control Parameters

In Chapter 4, we presented a list of control parameters that influence the attributes of the arcs and paths (see *Figure 4-9*). The purpose of this section is to examine the effects of changing select control parameters on the number of total arcs and paths, the heuristic computation time and ERF computation time, and the solution quality. We change *time periods per day* (*control*

Control Parameter	Value
C0: Begin Time	14-Mar-03-1200
C1: End Time	18-Mar-03-0000
C2: Time Periods per Day	12 time periods per day
C3: Min Dynamic Commodity Split Percent	25%
C4: Min Aircraft Residual Capacity Percent	20%
C5: Max Time Rerouted Aircraft Can Wait at New Aerial Port	2 time periods
C6: Max Miles for Rerouted Aircraft to New Aerial Port	500 miles
C7: Ground Time Periods for Rerouted Aircraft	1 time period
C8: Max Early Time Periods for Dynamic Commodity	70 time periods
C9: Max Late Time Periods for Dynamic Commodity	24 time periods
C11: Max Waiting Time Periods for Dynamic Commodity	24 time periods
C12: Max Transloads for Dynamic Commodity	1 transload

Table 5-1: Baseline ERF control parameters

Dynamic Commodity	Weight	APOE	APOD	ALT	Promised Time
0	15000 pounds	OERR	OETB	15 March 03, 0000 hours	17 March 03, 0000 hours
1	3000 pounds	ETAR	LIPA	15 March 03, 0000 hours	17 March 03, 0000 hours
2	20000 pounds	ETAR	EGUN	15 March 03, 0000 hours	17 March 03, 0000 hours
3	10000 pounds	ETAR	OASL	15 March 03, 0000 hours	17 March 03, 0000 hours
ICAO Code Dictionary: OERR – Arar OETB – Tabuk ETAR – Ramstein AB LIPA – Aviano AB EGUN – Mildenhall OASL – Afghanistan					

Table 5-2: ERF baseline dynamic commodities

parameter C2), *min dynamic commodity split fraction* (*control parameter C3*), *max miles for rerouted aircraft to new aerial port* (*control parameter C6*), *ground time periods for diverted aircraft* (*control parameter C7*), and *max number of transloads for dynamic commodity* (*control parameter C12*). The effects caused by changing the values of all the control parameters are summarized, except for the effects caused by changing *max time periods rerouted aircraft can wait for new aerial port operating hours (control parameter C10)*. In each run, we change a parameter independently of all others and we compare the results from the run to the results from a baseline run. *Table 5-1* presents the baseline values for the control parameters and *Table 5-2* presents the baseline dynamic commodities, identified by their weight, ICAO codes of their APODs and APOEs, ALT and promised times.

To compare each run to the baseline run, we use the following metrics: number of total arcs and paths, the objective function value, and the computation times. The number of total arcs and total paths indicates the size of the problem. The objective function value indicates the quality of the solution, because a lower cost objective function value reflects an improvement in the "desirability" of the solution. The computation time is measured in seconds and indicates the complexity of finding a solution.

5.1.1.1 Time Periods per Day

Time periods per day (*control parameter C2*) plays a key role in the precision of the model. Consider an aircraft that departs an aerial port at 0800 hours. When time periods per day equals one, the aircraft is modeled leaving the aerial port at 0000 hours. But when the time periods per day control parameter equals twelve, the aircraft is modeled leaving at its actual time of 0800 hours.

Hypothesis: Increasing the number of time periods per day causes a proportional increase in the number of total arcs. Because other control parameters are dependent upon the number of time periods per day, we change their values in proportion to the number of time periods per day. For example, suppose that time periods per day is increased from 12 to 24, then the number of time periods aircraft will wait for a commodity's ALT is also doubled to keep the number of hours aircraft will wait for a commodity's ALT constant.

Results: As the number of time periods per day increases, the number of arcs increases, as shown in *Figure 5-2*. However, the increase is less than proportional as predicted because the number of time periods per day does not indicate the fidelity in modeling the aircraft route, only the departure and arrival times. In order to capture accurately the routing of aircraft and commodities, the length of a time period must be smaller than the smallest flight or ground time of all aircraft. *Example 5-1* explains the model fidelity of aircraft routes.

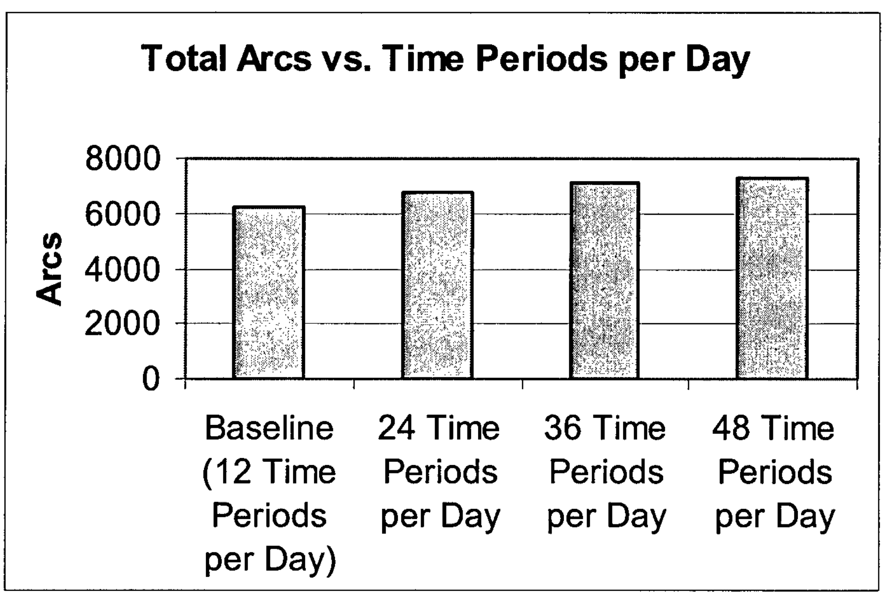

Figure 5-2: ERF total arcs vs. time periods per day

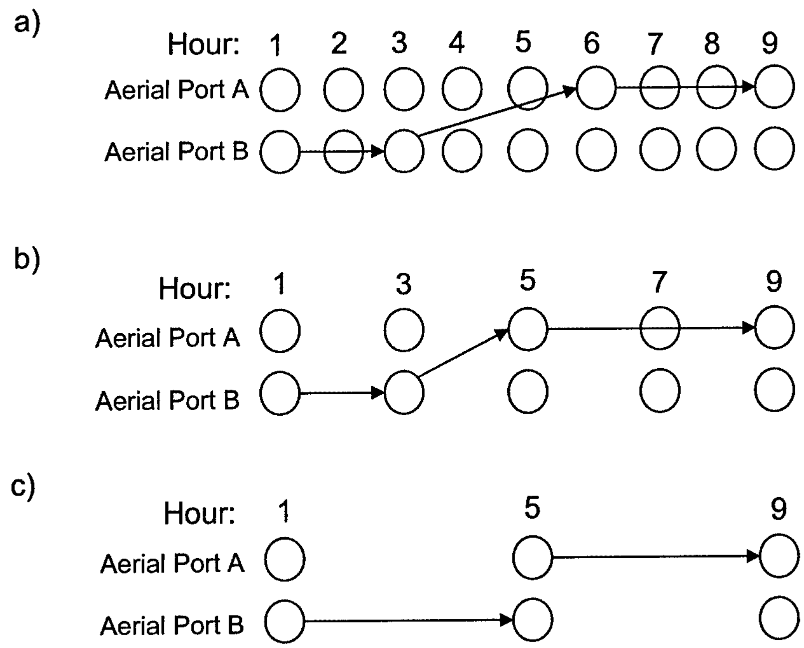

Figure 5-3: Model fidelity of aircraft routes

Example 5-1: *Consider an aircraft modeled in Figure 5-3a that is grounded at aerial port B from hour 1 to hour 3, travels from aerial port B to aerial port A from hour 3 to hour 6, and is grounded at aerial port A from hour 6 to hour 9. Suppose that this model represents the actual ground and flight times of the aircraft.*

Now consider the same aircraft to be modeled using twelve time periods per day in Figure 5-3b. Although the model has less fidelity, it still accurately captures the route of the aircraft and requires the same number of arcs.

Now consider the same aircraft to be modeled using six time periods per day in Figure 5-3. Because the flight time is less than four hours, the model does not accurately capture the route of the aircraft.

5.1.1.2 Min Dynamic Commodity Split Fraction

Min dynamic commodity split fraction (*control parameter C3*) represents the smallest split of a dynamic commodity when transported by different aircraft.

Hypothesis: This control parameter only affects the number of paths, because it does not affect aircraft routing. Increasing the value of this control parameter should decrease the number of total paths, therefore increasing the total cost of the solution.

Results: This control parameter does not affect the number of total arcs, as shown in *Figure 5-4a.* As the value of this control parameter decreases, the number of total paths increases, as shown in *Figure 5-4b.* The total cost increases as the value of this control parameter increases, as shown in *Figure 5-4c.*

5.1.1.3 Max Miles for Rerouted Aircraft to new Aerial Port

Max miles for rerouted aircraft to new aerial port (*control parameter C6*) dictates how far an aircraft can be rerouted from its originally scheduled route.

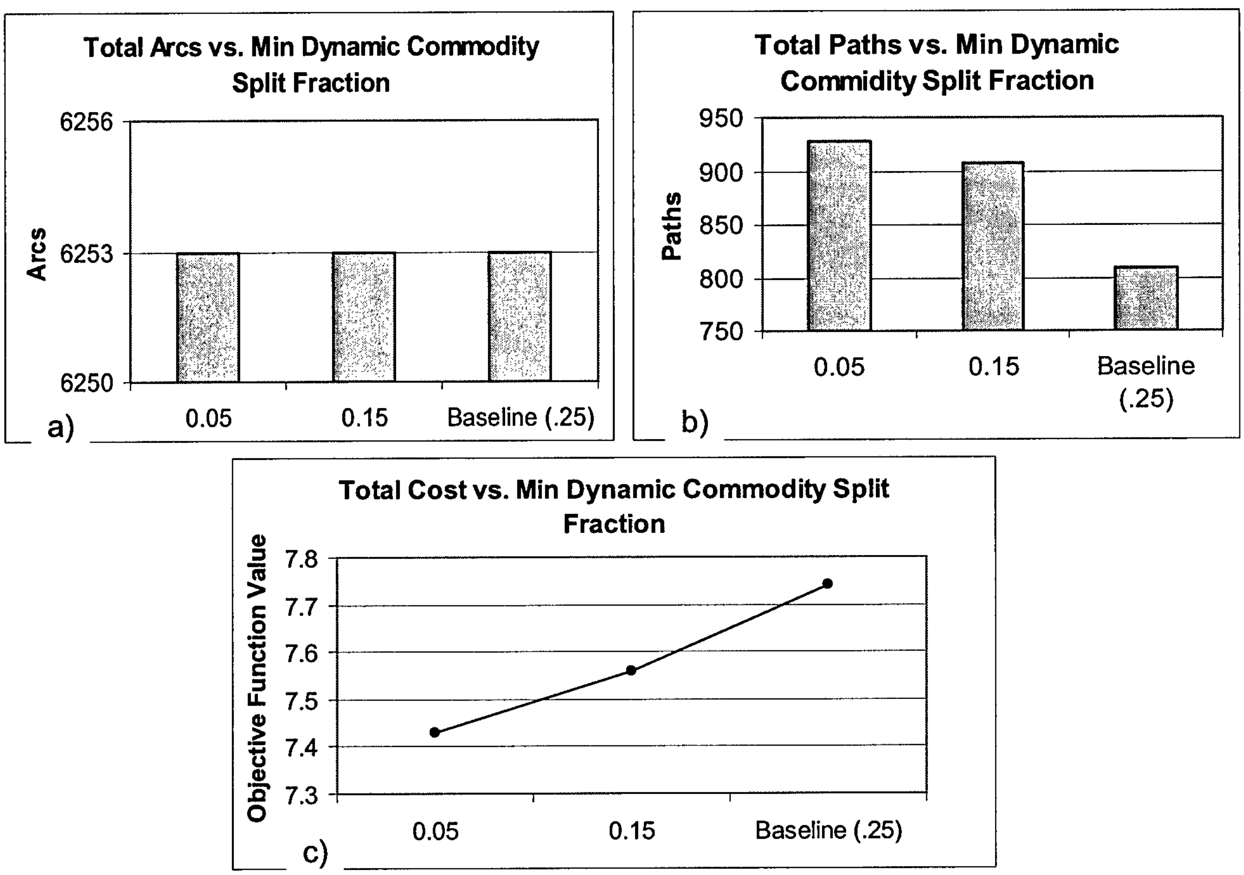

Figure 5-4: ERF model attributes vs. min dynamic commodity split fraction

Hypothesis: As this control parameter is increased, there are more opportunities to reroute aircraft, translating into an increase in the number of arcs and paths and a decrease in total cost.

Results: While there is a slight increase in the number of total arcs as this control parameter increases, the number of total paths significantly increases. The decrease in total cost is small at best, because the cost of flying further distances makes the new path opportunities undesirable. Once the max diversion for rerouted aircraft becomes larger than the maximum range of all aircraft types, increasing this parameter does not affect the number of arcs and paths. When this control parameter equals 300 miles, ERF is infeasible. *Figure 5-5* shows how the number of arcs and paths increase when max miles for rerouted aircraft is increased with only a modest decrease in total cost.

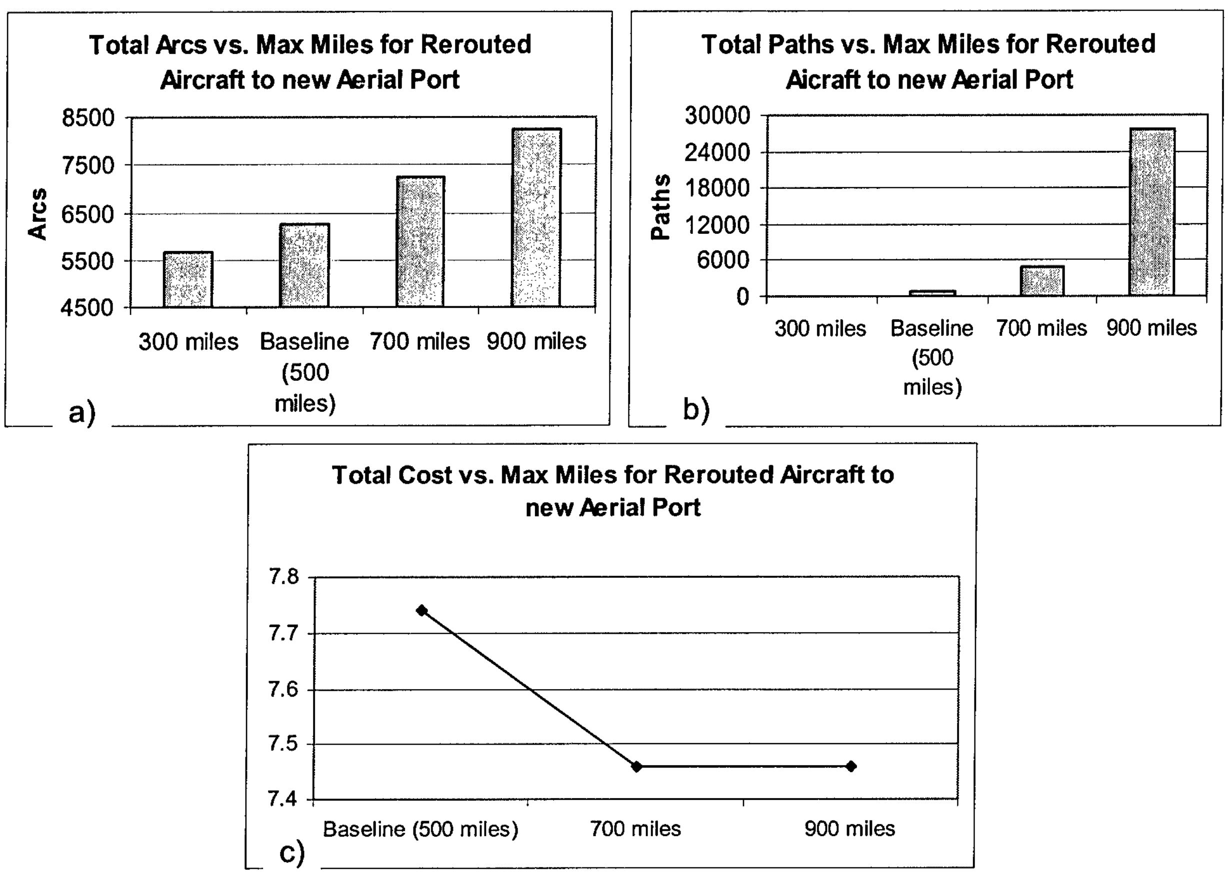

Figure 5-5: ERF model attributes vs. max miles for rerouted aircraft to new aerial port

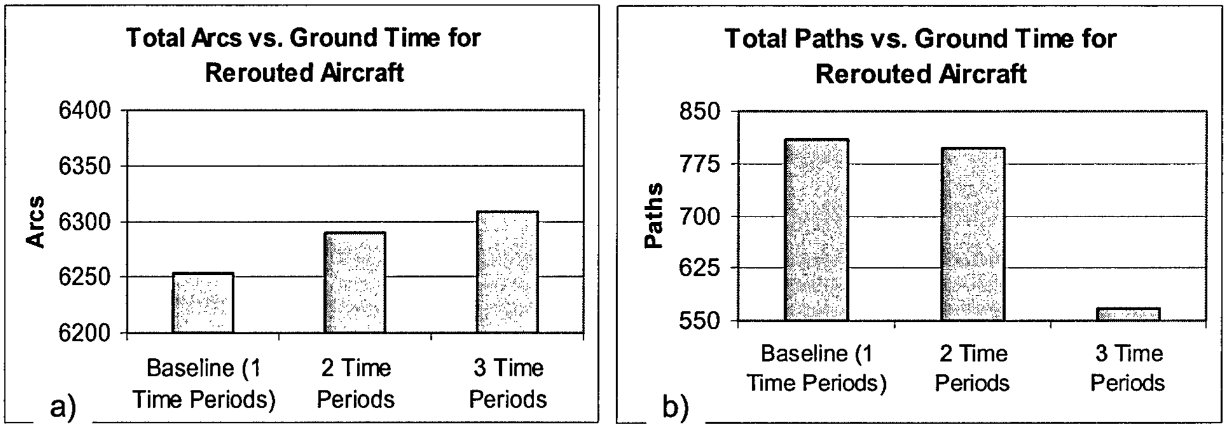

Figure 5-6: ERF model attributes vs. ground time for rerouted aircraft

5.1.1.4 Ground Time Periods for Rerouted Aircraft

Ground time for rerouted aircraft (*control parameter C7*) dictates the amount of time a rerouted aircraft must be at an aerial port for loading, unloading, and fueling.

Hypothesis: As aircraft spend more time on the ground, time is taken away that can be used to transport dynamic commodities, therefore an increase in the value of this control parameter should decrease the number of total arcs and paths.

Results: While the number of total paths decreases as predicted, the number of total arcs increases. This is due to additional ground arcs being generated that are needed to model the increased possibility of dynamic commodities being transloaded at the aerial ports. *Figure 5-6* shows the results of changing this control parameter.

5.1.1.5 Max Number of Transloads for Dynamic Commodity

Max number of transloads for dynamic commodity (*control parameter C12*) limits the number of aircraft that can be used to transport a single dynamic commodity.

Hypothesis: Because this control parameter only affects paths, as the value of this control parameter is increased, the number of total arcs should remain constant and the number of total paths should increase. Because AMC is constrained by the number of man-hours, the amount of cargo handling equipment, and the logistical complexity of transloads, allowing additional transloads is not advantageous for AMC, so the total cost should remain relatively constant.

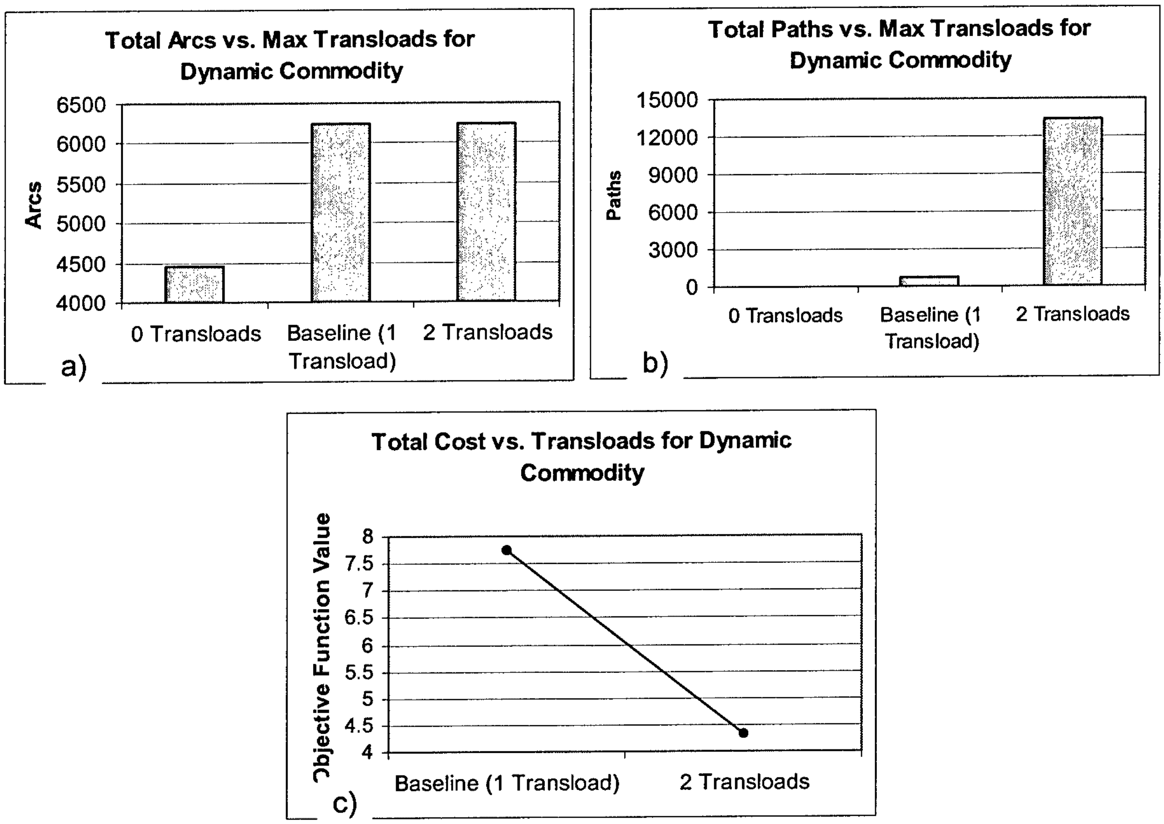

Figure 5-7: ERF model attributes vs. max transloads for dynamic commodity

Results: The number of total arcs remains constant, with the exception of zero transloads because ground arcs that model capacity of aerial ports, excluding APODs and APOEs, are not needed (see *Figure 5-7a)*. The number of total paths increases significantly when 2 transloads are allowed (see *Figure 5-7b*). The problem is infeasible with zero transloads, and there is a significant decrease in the total cost from one to two transloads, as shown in *Figure 5-7c*. This does not support our hypothesis, which implies that the baseline value of subjective weighting of transloads under this experiment is too small (see §5.1.3).

5.1.1.6 A Summary of the Effects caused by Changing the Values of Control Parameters

Table 5-3 presents how independently increasing the values of individual control parameters influences the number of total arcs and paths, the number of final arcs and paths, and the total cost. *Table 5-4* (page 114) presents the effects that varying the values of the control parameters have on the total cost.

Control Parameter	Number of Total Arcs	Number of Total Paths	Number of Final Arcs	Number of Final Paths	Total Cost
C0 (sooner)	Increase	Increase	Increase	Increase	Decrease
C1 (later)	Increase	Increase	Increase	Increase	Decrease
C2	Increase	Uncertain	Increase	Uncertain	Uncertain
C3	No Effect	Decrease	Decrease	Decrease	Increase
C4	No Effect	Decrease	Decrease	Decrease	Increase
C5	Increase	Increase	Increase	Increase	Decrease
C6	Increase	Increase	Increase	Increase	Decrease
C7	Increase	Decrease	Uncertain	Decrease	Uncertain
C8	Increase	Increase	Increase	Increase	Decrease
C9	Increase	Increase	Increase	Increase	Decrease
C11	Increase	Increase	Increase	Increase	Decrease
C12	No Effect (1)	Increase	Increase	Increase	Decrease
Notes: (1) One transload and greater					

Table 5-3: Overview of the effects of ERF control parameters

5.1.2 ERF Computational Performance

The purpose of this section is to investigate the computational performance of the arc and path creation heuristics and ERF and to identify values of control parameters that make the problem intractable. Computations were made using a Pentium IV 2.66 GHz Dell Computer with 512 MB of RAM.

As shown in the bottom row of *Table 5-5*, the generation of all paths and the arc and path reduction heuristics are significant contributors to computation time. Once the final arcs and final paths are identified, the ERF quickly finds a solution. Furthermore, ERF can be used to quickly explore changes in the subjective parameters (see §5.1.3) without re-creating arcs and again searching for paths, because only the constants in the ERF rows and objective function need to be changed.

C0		C1		C2		C3	
14-Mar-0000	7.74	17-Mar-1200	7.74	24 per day	7.11	.05	7.43
14-Mar-1200	7.74	18-Mar-0000	7.74	36 per day	8.56	.15	7.56
15-Mar-0000	7.74	18-Mar-1200	6.56	48 per day	8.93	.25	7.74
C4		**C5**		**C6**		**C7**	
.01	7.74	0 time periods	7.74	300 miles	Infeasible	1 time period	7.74
.05	7.74	2 time periods	7.74	500 miles	7.74	2 time periods	5.62
.1	Infeasible	4 time periods	5.32	900 miles	7.46	3 time periods	7.75
C8		**C9**		**C11**		**C12**	
6 time periods	Infeasible	0 time periods	13.96	12 time periods	11.28	0 transloads	Infeasible
38 time periods	7.74	12 time periods	7.74	24 time periods	7.74	1 transload	7.74
70 time periods	7.74	24 time periods	7.74	36 time periods	7.74	2 transloads	4.33

Table 5-4: The effects of ERF control parameters on total cost

While the arc and path reduction heuristics add a significant amount of computation time, not using the heuristics results in the IP becoming significantly difficult to solve. For example, we were unable to find a solution to a problem using the baseline data and control parameters within 8 hours. *Table 5-6* contrasts the number of rows and columns in the ERF with and without using the arc and path reduction heuristics.

Procedures	*Baseline*	*C1 = 18-Mar-1200*	*C6 = 700 miles*	*C6 = 900 miles*	*C12 = 2 transloads*
Model Aircraft from GDSS	3.5	3.5	3.5	3.5	4
Create All Arcs	3.5	4.5	4	5.5	3.5
Find All Paths	243	437	496	1828	5015
Arc and Path Reduction	34	42	488	5319	1225
Model Nodes	<1	<1	<1	<1	<1
Integer Program Preprocessing	9	5	33	331	135
Solve ERF	.453	.500	1.53	12.188	9.000

Table 5-5: Computation time (in seconds) with values of select ERF control parameters

Use of Path and Arc Reduction Heuristics	Number of Rows	Number of Columns
YES	10582	1677
NO	905571	7871

Table 5-6: Comparison of rows and columns in ERF

5.1.3 ERF Subjective Control Parameters

To account for subjective decisions that are made by the offshore cargo bookie, we proposed control parameters that provide relative "costs" (weights) for AMC operational characteristics (see §4.2.1.7). In this section, we analyze how the subjective control parameters affect the solutions.

Hypothesis: Changing the values of the subjective control parameters will change solution characteristics. For example, if the number of transloads is given a sufficiently high subjective weighting, we expect that the solution will have a minimal number of transloads.

Metric: Because changing the values of the subjective control parameters changes the objective function coefficients of the ERF, the objective function values of different solutions cannot be directly compared. Therefore, we compare solution characteristics to understand the type of the changes.

Subjective Control Parameters	Tested Values of the Subjective Control Parameters												
β	1	.1	16.1	32.1	48.1	64.1	80.1	96.1	112.1	128.1	144.1	160.1	176.1
γ	1	.1	16.1	32.1	48.1	64.1	80.1	96.1	112.1	128.1	144.1	160.1	176.1
ε	1	.1	16.1	32.1	48.1	64.1	80.1	96.1	112.1	128.1	144.1	160.1	176.1
α	1	.1	16.1	32.1	48.1	64.1	80.1	96.1	112.1	128.1	144.1	160.1	176.1
ω	.01	.01	2.41	4.81	7.21	8.01	10.41	12.81	15.21	200.1	202.5	204.9	207.3
λ	1	.1	16.1	32.1	48.1	64.1	80.1	96.1	112.1	128.1	144.1	160.1	176.1
ξ	1	.1	16.1	32.1	48.1	64.1	80.1	96.1	112.1	128.1	144.1	160.1	176.1
ζ	1	.1	16.1	32.1	48.1	64.1	80.1	96.1	112.1	128.1	144.1	160.1	176.1
Note: Dashed border outlines values that cause a change in the characteristics of the ERF baseline solution.													

Table 5-7: Values of ERF subjective control parameters that change the baseline solution

Time Period Depart	Arrive Time Period	Depart ICAO Code	Arrive ICAO Code	Aircraft Tail Number
Path 1: Transports 100% of Commodity 0 with a total weight of 15000 pounds and cost $c = 0$.				
23	24	OERR	OETB	23292A
Path 2: Transports 100% of Commodity 1 with a total weight of 3000 pounds and cost $c = 0$.				
8	9	ETAR	LIPA	N404LCC
Path 3: Transports 30% of Commodity 2 with a total weight of 6000 pounds and cost $c = 1.5$.				
16	20	ETAR	UAFM	N524UPC
20	22	UAFM	UAFM	N524UPC
22, 24, 27, 28	24, 27, 28, 29	UAFM	UAFM	GROUNDARC
29	31	UAFM	UAFM	23546S
31	35	UAFM	EGUN	23546S
Path 4: Transports 70% of Commodity 2 with a total weight of 14000 pounds and cost $c = 0$.				
22	23	ETAR	EGUN	01274T
Path 5: Transports 100% of Commodity 3 with a total weight of 10000 pounds and cost $c = 0.3$.				
8	11	ETAR	OTBH	30081S
11	13	OTBH	OTBH	30081S
13, 14, 15, 16	14, 15, 16, 17	OTBH	OTBH	GROUNDARC
17	19	OTBH	OTBH	10197A
19	20	OTBH	OAIX	10197A
20	21	OAIX	OAIX	10197A
21	22	OAIX	OASL	10197A

Table 5-8: Baseline ERF path solution

Results: Using the baseline control parameters, baseline dynamic commodities (see *Table 5-2*), and March 2003 data, the only subjective control parameters that affect the solution are λ and ξ, which represent the subjective weighting for the tardiness of a dynamic commodity and the number of transloads. The first column of values in *Table 5-7* are the baseline values and the dashed line encircles the values of λ and ξ that change the characteristics of the solution from the baseline solution. The baseline solution is shown in *Table 5-8*. For instance, 30% of commodity 2 is transported on path 3 and the remaining 70% is transported on path 4. On path 3, commodity 2 is first transported from its APOE by aircraft N524UPC and then remains on the ground at Manas Airport in Bishkek, Kyrgyzstan (UAFM) for four ground arcs, before it is transported by aircraft 23546S to its APOD. On path 4, commodity 2 is transported directly from its APOE to APOD by aircraft 01274T. For the values within the dotted lines, the solution

Time Period Depart	***Arrive Time Period***	***Depart ICAO Code***	***Arrive ICAO Code***	***Aircraft Tail Number***
Path 1: Transports 100% of Commodity 0 with a total weight of 15000 pounds and cost $c = 0$ for all values of λ and ξ within the dotted line of *Table 5-7*.				
23	24	OERR	OETB	23292A
Path 2: Transports 100% of Commodity 1 with a total weight of 3000 pounds and cost $c = 0$ for all values of λ and ξ within the dotted line of *Table 5-7*.				
8	9	ETAR	LIPA	N404LCC
Path 3: Transports 50% of Commodity 2 with a total weight of 10000 pounds and cost $c = 0$ for all values of λ and ξ within the dotted line of *Table 5-7*.				
16	17	ETAR	EGUN	60193A
Path 4: Transports 50% of Commodity 2 with a total weight of 10000 pounds and cost $c = 0$ for all values of λ and ξ within the dotted line of *Table 5-7*.				
22	23	ETAR	EGUL	01274T
23	24	EGUL	EGUL	01274T
24	25	EGUL	EGUN	01274T
Path 5: Transports 100% of Commodity 3 with a total weight of 10000 pounds and cost $c = 0.25$ for the values of λ within the dotted line of *Table 5-7* and cost $c = 24$ for the values of ξ within the dotted line of *Table 5-7*.				
8	11	ETAR	OTBH	30081S
11	13	OTBH	OTBH	30081S
13, 14, 15, 16	14, 15, 16, 17	OTBH	OTBH	GROUNDARC
17	19	OTBH	OTBH	10197A
19	20	OTBH	OAIX	10197A
20	21	OAIX	OAIX	10197A
21	22	OAIX	OASL	10197A

Table 5-9: Alternate ERF path solution

characteristics are nearly the same, with the values of λ and ξ producing different costs for path 5, as shown in *Table 5-9*. However, the similarity between the solution characteristics is coincidental, because the reasons for the two changes from the baseline solution characteristics caused by either values of λ within the dotted line or ξ within the dotted line are not the same, which is explained below.

With the baseline control parameters, all dynamic commodities have ALT of time period 6 and a promised time of time period 30. Not evident in *Table 5-8* is the fact that aircraft 01274T has been rerouted to fly from ETAR to EGUN to transport commodity 2 along path 4, 70% of commodity 2 completely fills the residual capacity of aircraft 01274T and the residual capacities of both aircraft N524UPC and 23546S are not completely filled by 30% of commodity 2. This implies that the ERF prefers to transport commodity 2 by aircraft 01274T, but has to use both aircraft N524UPC and 23546S due to the limited residual capacity of aircraft 01274T. Not evident in *Table 5-9* is the fact aircraft 01274T is rerouted to fly from EGUL to EGUN to transport commodity 2 along path 4, the residual capacities of both aircraft 60193A and 01274T are nearly filled by commodity 2 and aircraft 60193A is rerouted to fly from ETAR to EGUN to transport commodity 2 along path 3. For the values of λ within the dotted line, the reason for the change from the baseline solution characteristics is that the ERF reroutes aircraft 60193A to avoid the increased "cost" of commodity 2 being tardy along path 4. Because aircraft 60193A is already rerouted, the rerouting distance of aircraft 01274T can be reduced (it is less distance to be rerouted from EGUL to EGUN than from ETAR to EGUN). On the other hand, for the values of ξ within the dotted line, the ERF avoids the high "cost" of transloading commodity 2 between aircraft N524UPC and 23546S. Coincidently in this case, it produces the same changes in the solution characteristics as avoiding the high cost of being tardy.

5.1.4 Changing Data

Results using November 2002 GDSS data are compared with results using March 2003 GDSS data to investigate how AMC's operational environment affects solutions to the offshore cargo bookie's problems. The November 2002 GDSS data is from a time without a major contingency and the March 2003 GDSS data was gathered during a major force build up for Operation Iraqi Freedom. Because the notional decision guideline ranks decisions that use aircraft flying channel missions higher than the same type of decisions that use aircraft from other mission areas (see §2.2.6.2.2.3 and §4.1.3), the offshore cargo bookie is interested in how data affects the possibility of using aircraft flying channel missions to solve problems caused by disruptions in the channel route schedule.

Hypothesis: A solution using November 2002 GDSS data as input has more channel route missions and fewer contingency missions than a solution using March 2003 data.

Metrics: To measure the frequency of each mission type in the solution, the flight arcs for each mission type are counted. For aircraft that divert, the mission type of the diverted arcs is the same as the next non-diverting arc.

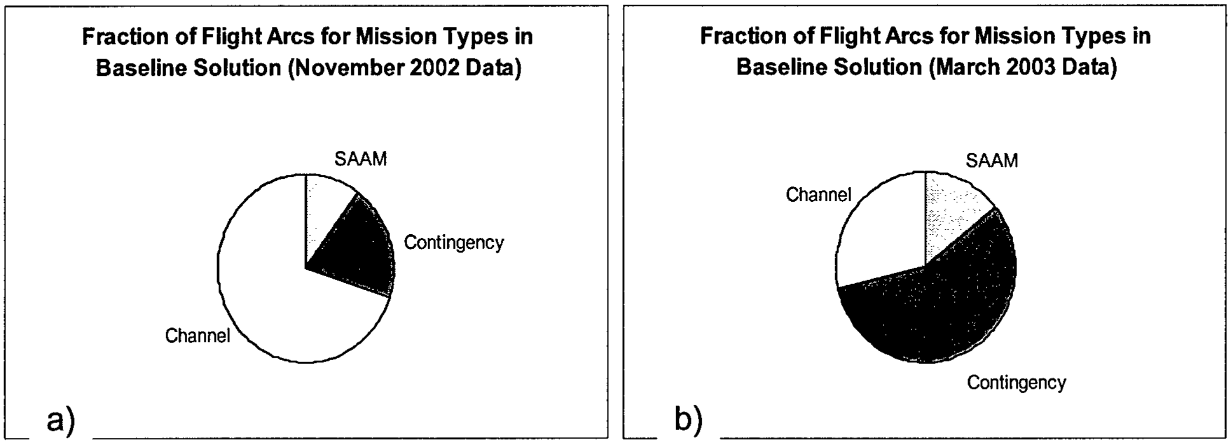

Figure 5-8: Proportions of mission areas in ERF solution

Results: As expected, the November 2002 GDSS data solution has a majority of channel route missions, while the March 2003 GDSS data solution has a majority of contingency missions, as shown by *Figure 5-8.*

5.1.5 Additional Dynamic Commodities

While the offshore cargo bookie rarely deals with more than four dynamic commodities, a decision support tool must be capable at processing more than four dynamic commodities when they do arise. In this section, we investigate the performance of the arc and path heuristics and ERF in processing more than four dynamic commodities. For each run in this section, we add one additional dynamic commodity from *Table 5-10*, with each successive run keeping all the commodities from the previous run.

Dynamic Commodity Number	Weight	APOE	APOD	ALT	Promised Time
4	10000 pounds	KCHS	OJHF	14 March 03, 0000 hours	17 March 03, 0000 hours
5	20000 pounds	KDOV	ETAR	14 March 03, 1200 hours	17 March 03, 1200 hours
6	10000 pounds	KDOV	EDDF	14 March 03, 0000 hours	17 March 03, 0000 hours
ICAO Code Dictionary: KCHS – Charleston AFB OJHF – Prince Hasan KDOV – Dover AFB ETAR – Ramstein AB EDDF– Frankfurt Main					

Table 5-10: Additional dynamic commodities

Procedures	Baseline	1 Extra Commodity	2 Extra Commodities	3 Extra Commodities
Time to Find All Paths	243 seconds	456 seconds	643 seconds	843 seconds
Time for Arc and Path Reduction Heuristics	34 seconds	66 seconds	78 seconds	253 seconds
ERF Solve Time	.453 seconds	.500 seconds	.563 seconds	1.093 seconds
Total Time	293 seconds	539 seconds	741 seconds	1135 seconds
Rows	10582	21575	37615	60283
Columns	1677	2885	3318	6600

Table 5-11: ERF attributes with additional dynamic commodities

Hypothesis: Additional dynamic commodities should increase the computational complexity of the model.

Metrics: To measure the computational complexity, we use CPU clock times, and the number of rows and columns in the ERF.

Results: The computational times are still practical, although significantly longer, as shown in *Table 5-11*. The ERF solution time remained practically the same, allowing the ERF to find alternate solutions quickly with changes in the subjective control parameters.

5.2 MOG Compliance Formulation Results

The MCF strategically delays aircraft on the ground to avoid a violation of MOG constraints. The MCF can be used by the offshore cargo bookie to identify MOG violations quickly that are caused by his/her decisions. The MOG master can use MCF to find solutions to MOG violations. *Figure 5-9* presents the algorithmic steps used in this section. The first two steps are used in the ERF testing software (see *Figure 5-1*). The first step models aircraft from GDSS data and the second step converts the flight legs found in the GDSS data into the arcs. Next, the algorithm models all the aerial ports found in the arcs. The MCF constraint rows and objective function are created in the next step. In the final step, MCF strategically delays aircraft to minimize the delay time of all aircraft in the AMC network, by solving the IP using XPress-MP 2003 software. In this section, we investigate the effects changes in values of control

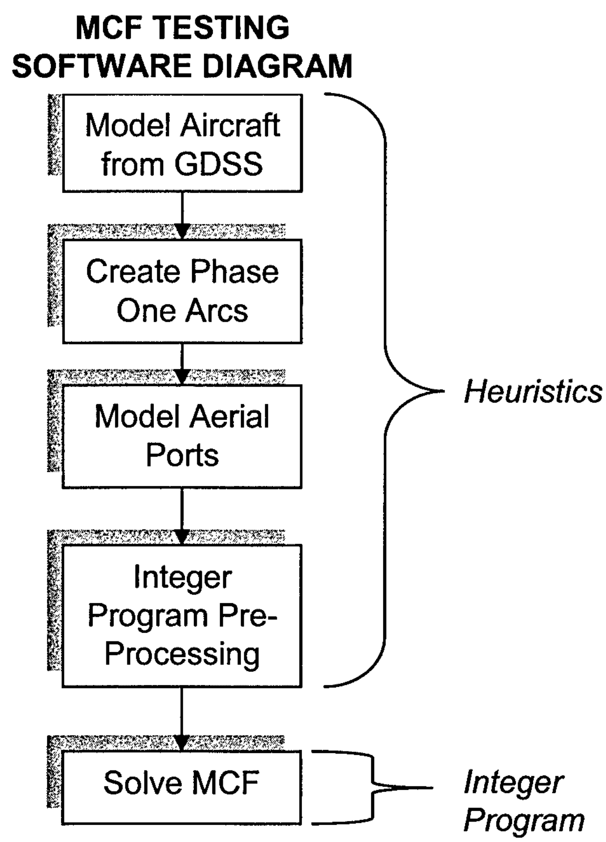

Figure 5-9: MCF testing software diagram

parameters have on the complexity of the problem and solution quality. We also investigate the effects subjective control parameters have on the solution characteristics. The data set includes 183 aircraft and 1347 arcs. The values of the aerial ports' MOG limits are synthesized.

5.2.1 MCF Control Parameters

In Chapter 4, we presented a list of control parameters that affect attributes of MCF (see *Table 4-2*). In this section, we change the *time periods per day* and *max delay time* control parameters, and examine the effects the changes have on the size of the model and the quality of the solution. To quantify the size of the model, we use the number of rows, number of columns, MCF preprocessing time, and MCF IP solution time. To quantify the quality of the solution, we use the objective function value (total cost) and IP-LP gap. For each run, the control parameters are changed independently of all others and we compare the results to a baseline, with values given in *Table 5-12*.

Control Parameter	Value
L0: Begin Time	14-Mar-03-1200
L1: End Time	18-Mar-03-0000
L2: Time Periods per Day	12 time periods per day
L3: Max Delay Time	30 time periods

Table 5-12: MCF baseline control parameter values

5.2.1.1 Time Periods per Day

Time periods per day (*control parameter L2*) sets the number of minutes for each time period in the model. This control parameter influences the fidelity of the model. Because the MOG master is concerned about delaying aircraft on a minute-by-minute basis while the offshore cargo bookie is concerned with how his/her decisions affect MOG levels, the two jobs might require different values for this control parameter.

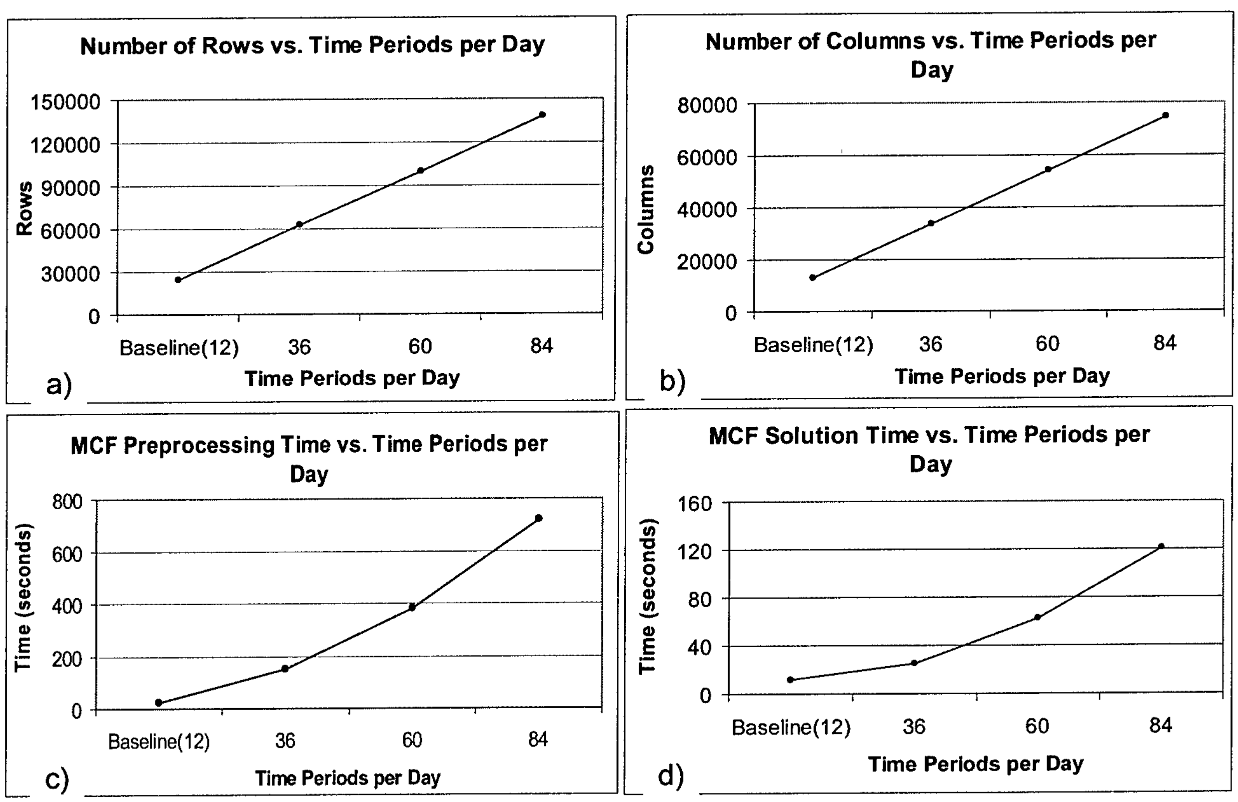

Figure 5-10: MCF attributes vs. time periods per day

Hypothesis: An increase in the number of time periods per day increases the complexity of the model.

Results: As *control parameter L2* increases, the number of rows, number of columns, preprocessing time and solution time increase, as shown by *Figure 5-10a-d.* The number of rows and columns increase linearly, while the preprocessing and solution time increase exponentially.

5.2.1.2 Max Delay Time Periods

Max delay time periods (*control parameter L3*) limits the number of time periods that an aircraft can be delayed on the ground beyond its originally scheduled departure time.

Hypothesis: An increase in the value of this control parameter from zero will cause the ERF to switch from being infeasible to being feasible. Once the MCF solution is feasible, the objective function value decreases as the control parameter increases, because increasing the potential delay of an individual aircraft provides more possibilities to reduce system-wide delay. At some value of max delay time periods, additional delay time does not improve the solution. An increase in max delay time periods increases the complexity of the problem, resulting in longer solution times.

Attributes	Max Delay Time Periods										
	3	6	7	8	9	10	11	12	24	30	72
Preprocessing Time in Seconds	3.86	3.83	3.95	3.83	4.05	4.08	4.10	4.02	4.67	4.88	10.02
Rows	3175	5538	6325	7112	7899	8686	9473	10260	19704	24426	57480
Columns	1712	2996	3424	3852	4280	4708	5136	5564	10700	13268	31244
Obj Function Value (ω = 0.01)	Infeas	Infeas	Infeas	Infeas	90.09	90.09	90.09	90.09	90.09	90.09	90.09
MCF Solution Time in Seconds (ω = 0.01)	N/A	N/A	N/A	N/A	1.297	2.906	2.468	2.875	3.719	11.781	32.031
Obj Function Value (ω = 100)	Infeas	Infeas	Infeas	Infeas	2703.59	2698.72	2698.72	2698.72	2698.72	2698.72	2698.72
MCF Solution Time in Seconds (ω = 100)	N/A	N/A	N/A	N/A	.407	.312	.344	.766	.969	1.172	2.813

Table 5-13: The effects of varying ω on MCF model attributes

Results: As shown in *Table 5-13*, the MCF is infeasible up to eight max delay time periods, because there is not enough "flexibility" to avoid violating the MOG limits. For ω = .01, which weights the AMC attribute of the number of time periods a mission is scheduled beyond the begin time (see §4.2.2.2), the objective function value is constant for max delay time periods ≥ 9. For $\omega = 100$, the value of the objective function is slightly higher when the value of max delay time periods is 8, then is reduced and constant for max delay time ≥ 9. For $\omega = 100$, the MCF "wants" to delay individual aircraft for more than 8 time periods. Soulution time is shorter for $\omega = 100$ than for $\omega = 0.01$.

5.2.2 MCF Subjective Control Parameters

MCF subjective control parameters influence the characteristics of MCF solutions by weights in the objective function (see §4.2.2.2). In this section we explore the effects from changes in subjective control parameters on solution characteristics. To demonstrate some of the possible effects, we change the value of the subjective control parameter ε, the subjective weighting for the priority of the aircraft's mission, to an extreme value of $\varepsilon = 100$, then compare the characteristics of the solution to the characteristics of the baseline solution.

Table 5-14 presents the solution characteristics of MCF for $\varepsilon = 0.01$ (baseline) and ε = 100. Note that the only differences will be found in the departure and arrival times. The first two columns are the ICAO codes for the aerial ports in the aircraft routes and the last three columns present the attributes of the arcs. As an example, consider aircraft 40060B, which requires diplomatic clearances (DIPS) on its single flight arc with a priority of 1B1. In the baseline solution, aircraft 40060B is scheduled to depart aerial port LERT at time period 0 and then fly to aerial port KCEF to arrive at time period 4. When $\varepsilon = 100$, the aircraft is delayed an additional time period and scheduled to depart aerial port LERT at time period 1.

Because more weight is placed on the priority of aircraft and relatively less weight on DIPS when $\varepsilon = 100$, aircraft requiring DIPS (i.e., aircraft 40060B, 50102A, and 90002B) are delayed beyond the baseline solution and aircraft not requiring DIPS (i.e., aircraft 10880E, 56712T, 80808T, and ZH874T) have less delays than the baseline solution. In other words, aircraft requiring DIPS have additional delays when $\varepsilon = 100$ to allow for less delays in significantly more flight arcs of other aircraft.

Aircraft	Depart ICAO Code	Arrive ICAO Code	Depart Time Period (ε=1)	Arrive Time Period (ε=1)	Depart Time Period (ε=100)	Arrive Time Period (ε=100)	Priority	DIPS	HAZMAT
10880E	LERT	LERT	0	3	0	2	Aircraft Ground Arc		
	LERT	LPLA	3	4	2	3	1B3	No	No
	LPLA	LPLA	4	5	3	4	Aircraft Ground Arc		
	LPLA	LERT	5	6	4	5	1B3	No	No
40060B	LERT	LERT	0	0	0	1	Aircraft Ground Arc		
	LERT	KCEF	0	4	1	5	1B1	Yes	No
50102A	OOMA	OOMA	0	0	0	1	Aircraft Ground Arc		
	OOMA	EDDF	0	5	1	6	1B1	No	No
56712T	OOMA	OOMA	0	2	0	1	Aircraft Ground Arc		
	OOMA	OOTH	2	3	1	2	1B1	No	No
	OOTH	OOTH	3	4	2	3	Aircraft Ground Arc		
	OOTH	OOMS	4	5	3	4	1B1	No	No
	OOMS	OOMS	5	6	4	5	Aircraft Ground Arc		
	OOMS	OOMA	6	7	5	6	1B1	No	No
80808T	OKBK	OKBK	0	6	0	3	Aircraft Ground Arc		
	OKBK	OETB	6	8	3	5	1B1	No	No
90002B	OKBK	OKBK	0	3	0	6	Aircraft Ground Arc		
	OKBK	OETB	3	7	6	10	1B1	Yes	No
ZH874T	OMFJ	OMFJ	0	2	0	0	Aircraft Ground Arc		
	OMFJ	OKBK	2	3	0	1	1B1	No	No
	OKBK	OKBK	3	4	1	2	Aircraft Ground Arc		
	OKBK	OTBH	4	5	2	3	1B1	No	No
	OTBH	OTBH	5	6	3	4	Aircraft Ground Arc		
	OTBH	OMFJ	6	7	4	5	1B1	No	No

Table 5-14: Difference in characteristics of two MCF solutions

5.3 Summary

This chapter examines the effects of the control parameters and subjective control parameters on the model complexity and solution quality, and for the ERF, the effect of changing input data sets on solution properties. Because of the large amount of data and a two hour time constraint, the offshore cargo bookie usually implements his/her initial solution. This chapter illustrates how the models in this thesis can be used to help the offshore cargo bookie find and analyze alternate solutions to disruptions in the channel route schedule. It also identifies limitations of the models by presenting instances where the models become impractical. In Chapter 6, we present how these models can be transitioned into AMC's operations.

6 Towards a Decision Support Tool

In Chapter 5, we described experiments that demonstrate ERF and MCF's ability to re-plan during the execution month with the flexibility to allow for "what-if" analysis. This is the first step in showing that an optimization-based decision support tool can aid offshore cargo bookies in finding solutions to problems caused by disruptions in the channel route schedule.

We use this chapter to describe how this can be transitioned into an operational decision support tool. We split this chapter into four sections. In the first section, we describe a notional decision support tool. In the second section, we discuss enhancements to the research presented in this thesis that would enable the development of an operational decision support tool. In the third section, we present how the decision support tool could be extended to help other personnel besides the offshore cargo bookie, such as the MOG master, commercial scheduler, and CONUS cargo bookie. In the final section, we present the challenges that must faced by AMC to achieve the vision of a decision support tool.

6.1 Description of the Decision Support Tool

The purpose of a decision support tool is not to replace the operator by automating decisions, but to allow the offshore cargo bookie to make well-informed decisions with high overall value to AMC's operations. The models presented in Chapter 4 can be used to re-plan a portion of the channel route schedule. In this way, the schedule before and after the re-planned portion is not altered, although the schedule after the re-planned portion might be delayed. *Figure 6-1* presents how this "splicing" is done. A decision support tool can be a drop down menu in a current database interface, such as GATES. Once solutions are found using the decision support tool, the offshore cargo bookie should have a graphical user interface (GUI) that provides the ability to analyze different solutions, conduct "what-if" analysis, and customize the solution to include information that cannot be captured in the input data set. The solution would be valuable in negotiating with the barrelmaster and other mission areas for additional capacity.

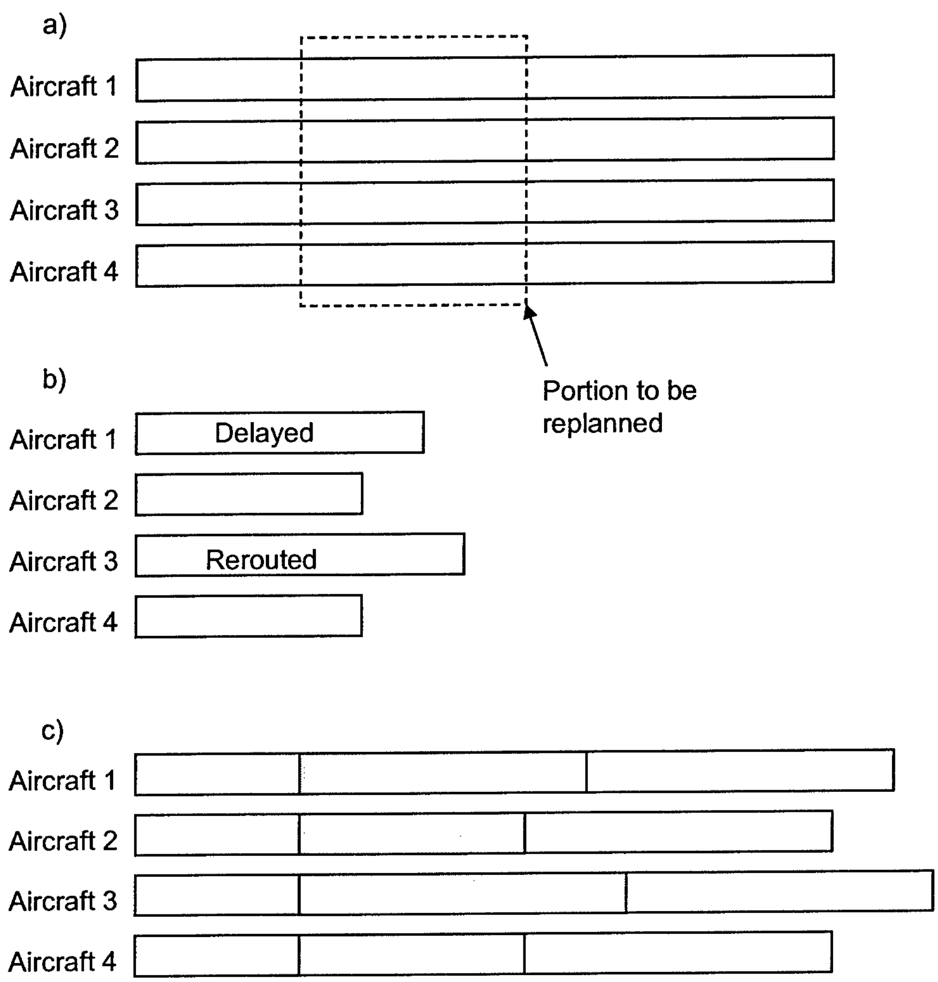

Figure 6-1: The "splicing" and re-planning of the channel route schedule

6.2 Enhancing the Models

In this section we present improvements to the models of Chapter 4 that will be useful for the offshore cargo bookie in a decision support tool. These improvements also demonstrate the flexibility of the models.

6.2.1 Updating Subjective Equations

The subjective equations presented in Chapter 4 (i.e., equations *4.11*, *4.12* and *4.20*) provide the value of the coefficients in the ERF and MCF objective functions. The subjective weight in the equations can be changed by the offshore cargo bookie to search for solutions with desired attributes. The structure of the equations can be easily changed to allow for changes in AMC operations. For example, the cost of rerouting aircraft by mission types can be an additional weight. The subjective equations presented in Chapter 4 assume specific functional forms and additional research will be needed to refine the functions so that they accurately depict operations.

6.2.2 Incorporating the Sequence Listing

The channel development and analysis division (see §2.1.4.5 and §2.2.6.2.2) is responsible for converting validated channels into specific allowable origin-destination pairs for aircraft flight legs. While the offshore cargo bookie usually follows the sequence listing, deviations from the sequence listing increases the complexity of rerouting aircraft. As an option in the decision support tool, the solution can be forced to be consistent with the sequence listing, which consequently limits the number of arcs and paths that feed into the ERF. Incorporating the sequence listing into the models can be easily done by having the arc creation heuristics reject arcs that are not consistent with the sequence listing.

6.2.3 Streamlining the Arc and Path Reduction Heuristics

As demonstrated in Chapter 5, arc and path reduction heuristics require the majority of the computation time (see §5.1.2). Alternative heuristics should be explored to find ways to reduce computation time. In addition, computer programming techniques exist that might reduce computation time. For example, the currently implemented arc and path reduction heuristics use the Java Vector class to manage data, which is notoriously slow.

6.2.4 Control Parameters for Each Aircraft and Dynamic Commodities

The control parameters of the ERF and MCF presented in Chapter 4 specify values for all aircraft and dynamic commodities (see §4.2.1.2 and §4.2.2.1). These values could be specified for different aircraft types, individual aircraft and/or specific commodities. By having more control over the control parameters, the offshore cargo bookie would be in a better position to tailor the models to account for current operational conditions.

6.2.5 Include Option to Use Hours instead of Miles

In many cases, AMC operators use the number of hours that an aircraft is rerouted rather the number of miles. This is because maintenance intervals are based on the number of hours that components (e.g., engines, fuel system) are in operation. Also environmental factors, such as wind, might make a mileage metric inaccurate. Hours can be easily included into the arc creation heuristics by limiting rerouted arcs to a certain number of time periods.

6.3 Extending the Decision Support Tool

The vision of embedding these models within a decision support tool could extend beyond the responsibilities of the offshore cargo bookie. The models directly affect the jobs of the MOG master and CONUS cargo bookie (see §2.2.6.2.1.6 and §2.2.6.2.2). The MOG master could use a decision support tool to find solutions to MOG violations on an hourly basis. In fact, Excel macros developed by XON can track the number of aircraft at each aerial port. When predetermined MOG levels are violated, the software alerts the operator of the violation. The MCF can be embedded in the software to find solutions to MOG violations.

The CONUS cargo bookie could use a decision support tool to find solutions to cargo problems caused by disruptions at CONUS APOEs. The models presented in this thesis can be used to analyze the options of the CONUS cargo bookie and justify the CONUS cargo bookie's request for additional organic and expansion-buy aircraft. When the CONUS cargo bookie does request additional organic and expansion-buy aircraft, he/she can know which potential routes would be beneficial for the offshore cargo bookie.

6.4 Challenges Faced by AMC

There are a number of challenges in developing an optimization-based decision support tool to effectively support AMC operations. These are illustrated through cases of the Barrel Allocator, software that supports the barrelmaster by allocating aircraft to AMC's mission areas based on JCS priority codes [6]. While the Barrel Allocator worked well in controlled experiments before its implementation, the barrelmaster has not found it useful in day-to-day operations. In this section, we present three notional causes as to why the barrelmaster has not adopted the Barrel Allocator, which provides insight into the challenges that exist for the implementation of any optimization-based decision support tools.

6.4.1 Data

An optimization-based decision support tool requires timely and accurate information. In current AMC operations, GDSS tends to be a "push" system. A "push" system is defined as information being input into the database after the data is collected. A "pull" system, on the other hand, allows operators to use data from the database in real-time. Therefore, information that could be useful in supporting AMC operators during mission execution is not available until after the fact, if ever. As an example, the MOG levels of aerial ports are rarely known by AMC operators in real-time and much of contingency mission planning is performed on grease boards, with the schedule put into GDSS after the start of mission execution. In addition, optimization-based decision support tools are most effective when database information is accurate. One way to reduce user input errors is to simplify input software, integrate methods that verify or automate input information and issue specialized input devices for operators that do not have easy access to a computer.

6.4.2 Software Integration

Because much of the software at AMC has evolved beyond their original purpose, the different GDSS interface tools (e.g., GATES and CAMPS) sometimes have difficulty in exchanging data. An example of this is the fact that the Barrel Allocator can sometimes only transfer data from CAMPS, but not to CAMPS, so the barrelmaster must manually input the solution from the Barrel Allocator into CAMPS. The same difficulty sometimes arises when data can only be transferred from GDSS to CAMPS and is unable to be transferred from CAMPS to GDSS. This issue has become a high priority and the next incarnation of GDSS, GDSS 2, scheduled to be released before fiscal year 2005, is planned to alleviate many of the data integration issues.

6.4.3 JCS Priority System

During the first Persian Gulf War, the Air Force, Army, and Navy were coding nearly half of their cargo with 999, the highest priority. Because much of the cargo should have been transported by ship, the amount of cargo needing air transportation was thirty percent above the amount of airlift capacity available. This would have quickly backlogged all cargo, including the cargo with 999 priority. Fortunately, the JCS stepped in and sent diversion teams that reprioritized the cargo [21]. The JCS mission priority system is also subject to these types of problems. This poses a challenge to any optimization-based tool building on the JCS mission priority system. Although the Barrel Allocator gives near-optimal solutions based on the JCS priority of aircraft missions, the barrel master often changes or discards the solution because he/she knows from experience the "true" JCS priorities.

7 Summary and Future Research

The focus of the research in this thesis is to show the technical feasibility of an optimization-based approach to find solutions to support Air Mobility Command's (AMC) channel route schedule execution. Current operations are mostly manual, with few opportunities for personnel at AMC to find more than one solution because of large amounts of information and an urgency to find a solution. To overcome these challenges, we use optimization-based models to quickly find good solutions that allow for "what-if" analysis. This chapter provides a summary of the research presented in this thesis and suggestions for future work.

7.1 Thesis Summary

Chapter 1 presents the motivation for this research. We describe the United States Transportation Command (USTRANSCOM) and AMC's role within USTRANSCOM. AMC allocates aircraft among five mission areas – contingency, exercises, Joint Airborne/Air Transportability Training (JA/ATTs), Special Assignment Airlift Mission (SAAMs), and channel routes. Channel route missions transport military personnel and cargo in support of military operations. During execution of the channel route schedule, individual channel route missions are often disrupted, because channel routes might be lower priority than the other mission areas or other disruptions can occur such as maintenance problems, weather and unexpected amounts of cargo needing transportation. The operators of AMC must continuously find solutions to the problems that result from these disruptions.

Chapter 2 describes the key operational elements and procedures of AMC that puts this research into context. We describe the AMC network, which is the physical system that is made up of military and commercial aircraft, aircrew, and aerial ports. We then describe the channel route planning and execution process. We define the scope of our research to be finding solutions to problems caused by disruptions in the execution of channel route missions. Finding solutions to problems caused by disruptions is challenging because there is large amount of information and an urgency to find solutions. Currently, AMC personnel rely on a mostly manual process to find solutions.

Chapter 3 presents a technical background on network optimization models, concepts described in Nielsen [24] and a literature review of models that apply to re-planning during the execution of commercial airline schedules. Two of the network optimization models are the Service Network Design Formulation (SND-F) model and the Multi-Airport Ground-Holding Problem Formulation (MAGP-F). The SND-F has both arcs and paths as decision variables and the MAGP-F strategically delays aircraft on the ground to reduce system wide congestion. Nielsen [24] uses composite variables to create the channel route schedule and his optimization model has an extremely tight LP relaxation. The commercial airline literature review shows the subjective decisions that must be made in schedule execution.

Chapter 4 presents an analysis of the current solution-finding process for disruptions that occur in channel route execution. We analyze a notional guideline that is used to make decisions. While it is best to produce a solution that simultaneously considers all information, we decompose the process to make it tractable. From the decomposition, we create heuristics and formulate models interface through arc and path data. The first model, the Execution Recovery Formulation (ERF), is based on the SND-F and is motivated by the problem of unexpected amounts of channel cargo in need of airlift, such as cargo that was underestimated and cargo that must be unloaded from aircraft that requires unscheduled maintenance. The ERF finds solutions to excess cargo through rerouting aircraft, delaying aircraft, leveraging underutilized aircraft from other mission areas, and using more than one aircraft to transport cargo. The second model, the Maximum on Ground Compliance Formulation (MCF) based on the MAGP-F, strategically delays aircraft at an aerial port to ensure that the number of aircraft at each aerial port system-wide does not exceed each aerial port's allowable number of aircraft. A third model, Aircraft Purchase Formulation (APF), which is left for future research, is envisioned to have the capability to decide on the minimum cost aircraft and the aircraft' routes to transport any cargo that cannot be accommodated by the ERF (i.e., if ERF is infeasible).

In both the ERF and MCF, we model the subjectivity of the decisions by weighting desired characteristics of the solution. The constants in these equations can be changed for "what-if" analysis. The ERF and MCF have additional flexibility through parameters of our model of AMC operations.

Chapter 5 presents results and analysis of both the computational and solution characteristics of the ERF and MCF. We demonstrate the practicality of our approach for use in decision support for operators during execution of channel route missions. They are flexible, are able to quickly process large amounts of data and allow for analysis of multiple solutions.

Chapter 6 presents how the research in this thesis can be transitioned into a decision support tool. The decision support tool is envisioned to be part of current software at AMC, possibly within a pull-down menu that allows AMC operators to conduct "what-if" analysis and removes the painstaking manual process of searching through data and allows for analysis of alternate solutions. We list improvements to the models that can make them more useful for AMC operators. Finally, we present the challenges that AMC must overcome before the models can be implemented into the current system.

7.2 Future Research

In Chapter 6, we presented improvements that can be made to the models developed in Chapter 4, making them more useful for AMC operators. In this section we present models that remain for future research.

THE AIRCRAFT PURCHASE FORMULATION

When the ERF is infeasible, there is a need for additional aircraft capacity. The aircraft purchase formulation (APF), discussed in Chapter 4, is a model that can be used to decide what additional organic aircraft should be acquired, what commercial aircraft should be leased through expansion-buy, the routes of those aircraft, and whether aircraft should unload their cargo to transport other higher priority cargo. The output from this model is a set of additional arcs and paths that can feed into the ERF to make it feasible.

PROBABILISTIC MODEL

During the execution of aircraft missions, operators at AMC must make decisions under uncertainty. Three examples are the reliability of aircraft, weather, and the amount of cargo needing transportation. AMC uses the maintenance reliability factor as a metric for the expected reliability of different aircraft types. The amount of cargo needing transportation can be estimated using past data and operator estimations. This information should be integrated with the models presented in Chapter 4 to increase the robustness of the solutions.

AREA OF CONTINGENCY HUB AND SPOKE NETWORK

In current contingencies in Iraq and Afghanistan, cargo that arrives to the area of the contingency is unloaded at a central location due to the danger presented by the contingency. Only a limited number of aircraft are allowed to fly within the area of the contingency to transport the cargo to its final destination. Other constraints include the number of available aircrew and inaccessibility of some aerial ports due to the enemy's anti-aircraft weaponry. Because cargo might be forced to remain at the central location for extended periods of time, the model presented in this thesis could have increased flexibility of delaying this cargo at other aerial ports.

Appendix A: Formulations and Equations

$$\text{MCNF-A=} \qquad \min \sum_{k\in K}\sum_{(i,j)\in A} c_{ij}^k x_{ij}^k \tag{3.1}$$

$$s.t. \qquad \sum_{k\in K} x_{ij}^k \le u_{ij} \qquad \forall (i,j)\in A, \tag{3.2}$$

$$\sum_{\{j:(i,j)\in A\}} x_{ij}^k - \sum_{\{j:(j,i)\in A\}} x_{ji}^k = \begin{cases} b_i^k > 0, \text{ if } i = O(k) \\ b_i^k < 0, \text{ if } i = D(k) \\ 0, \text{ otherwise} \end{cases} \qquad \forall i\in N, k\in K, \tag{3.3}$$

$$x_{ij}^k \ge 0 \qquad \forall (i,j)\in A, k\in K. \tag{3.4}$$

$$\text{MCNF-P =} \qquad \min \sum_{k\in K}\sum_{p\in P^k} c_p^k x_p^k \tag{3.5}$$

$$s.t. \qquad \sum_{k\in K}\sum_{p\in P^k} \delta_{ij}^p q^k x_p^k \le u_{ij} \qquad \forall (i,j)\in A, \tag{3.6}$$

$$\sum_{p\in P^k} x_p^k = 1 \qquad \forall k\in K, \tag{3.7}$$

$$x_p^k \ge 0 \qquad \forall k\in K, p\in P. \tag{3.8}$$

$$SNDP-F= \quad \min \sum_{k\in K}\sum_{p\in P^k} c_p^k x_p^k + \sum_{f\in F}\sum_{(i,j)\in A} d_{ij}^f y_{ij}^f \tag{3.9}$$

$$s.t. \quad \sum_{k\in K}\sum_{p\in P^k} \delta_{ij}^p b^k x_p^k \le u_{ij}^f y_{ij}^f \qquad \forall (i,j)\in A, \tag{3.10}$$

$$\sum_{p\in P^k} x_p^k = 1 \qquad \forall k\in K, \tag{3.11}$$

$$\sum_{\{j:(i,j)\in A\}} y_{ij}^f - \sum_{\{j:(j,i)\in A\}} y_{ji}^f = 0 \qquad \forall i\in N, f\in F, \tag{3.12}$$

$$x_p^k \ge 0 \qquad \forall k\in K, p\in P^k, \tag{3.13}$$

$$y_{ij}^f \in \{0,1\} \qquad \forall (i,j)\in A^f, \forall f\in F. \tag{3.14}$$

$$\text{MAGHP-F=} \quad \min \sum_{f\in F}\left[(c_f^g - c_f^a)\sum_{t\in T_f^d} t(w_{f,t}^1 - w_{f,t-1}^1) + c_f^a \sum_{t\in T_f^a} t(w_{f,t}^2 - w_{f,t-1}^2) + (c_f^a - c_f^g)h_f - c_f^a r_f \right] \tag{3.15}$$

$$s.t. \quad \sum_{f:t\in T_f^d} (w_{f,t}^1 - w_{f,t-1}^1) \le D_{k,t} \qquad \forall k\in K, t\in T, \tag{3.16}$$

$$\sum_{f:t\in T_f^a} (w_{f,t}^2 - w_{f,t-1}^2) \le A_{k,t} \qquad \forall k\in K, t\in T, \tag{3.17}$$

$$w_{f,t}^2 - w_{f,t-(r_f-h_f)}^1 \le 0 \qquad \forall f\in F, t\in T_f^a, \tag{3.18}$$

$$w_{f,t}^1 - w_{f',t-o_{f'}}^2 \le 0 \qquad \forall (f',f)\in C, t\in T_f^d, \tag{3.19}$$

$$w_{f,t}^1 - w_{f,t-1}^1 \ge 0 \qquad \forall f\in F, t\in T_f^d, \tag{3.20}$$

$$w_{f,t}^2 - w_{f,t-1}^2 \ge 0 \qquad \forall f\in F, t\in T_f^a, \tag{3.21}$$

$$w_{f,t}^1, w_{f,t}^2 \in \{0,1\} \qquad \forall f\in F, t\in T. \tag{3.22}$$

$$\text{ERF} = \min \sum_{k\in K}\sum_{p\in P^k} c_p^k x_p^k + \sum_{f\in F}\sum_{(i,j)\in A^f} d_{ij}^f y_{ij}^f \tag{4.1}$$

s.t.

$$\sum_{k\in K}\sum_{p\in P^k} \delta_{ij}^p b^k x_p^k \le u_{ij}^f y_{ij}^f \qquad \forall f\in F, \forall (i,j)\in L^f, \tag{4.2}$$

$$\sum_{p\in P^k} x_p^k = 1 \qquad \forall k\in K, \tag{4.3}$$

$$x_p^k - z_p^k s \ge 0 \qquad \forall k\in K, p\in P^k, \tag{4.4}$$

$$-x_p^k + z_p^k \ge 0 \qquad \forall k\in K, p\in P^k, \tag{4.5}$$

$$\sum_{\{j:(i,j)\in A^f\}} y_{ij}^f - \sum_{\{j:(j,i)\in A^f\}} y_{ji}^f = 0 \qquad \forall i\in N, f\in F, \tag{4.6}$$

$$y_{ij}^f \in \{0,1\} \qquad \forall f\in F, \forall (i,j)\in A^f, \tag{4.7}$$

$$x_p^k \ge 0 \qquad \forall k\in K, p\in P^k, \tag{4.8}$$

$$z_p^k \in \{0,1\} \qquad \forall k\in K, p\in P^k. \tag{4.9}$$

$$d_{ij}^f = \beta * DIPS_{ij}^f + \gamma * HAZ_{ij}^f + \varepsilon / PRTY_{ij}^f + \alpha * DIST_{ij}^f + \omega / (TIME_{ij}^f + 1) \tag{4.10}$$

$$c_p^k = \frac{\lambda * TARDY_p^k + \xi * PLNCHG_p^k}{\zeta * PRTY^k} \tag{4.11}$$

$$\text{MCF} = \quad min \sum_{g \in G} \left[c_g \sum_{t \in T_g^d} (t - d_g)(w_{g,t}^d - w_{g,t-1}^d) \right] \tag{4.12}$$

s.t.

$$\sum_{g \in G^e : t \in T_g^a, t \notin T_g^d} m_g w_{g,t}^a + \sum_{g \in G^e : t \in T_g^a, t \in T_g^d} m_g (w_{g,t}^a - w_{g,t}^d)$$

$$+ \sum_{g \in G^e : t \notin T_g^a, t \in T_g^d} m_g (1 - w_{g,t}^d) \le M_e(t) \qquad \forall e \in E, \tag{4.13}$$

$$w_{g,t+o_g}^d - w_{g,t}^a \le 0 \qquad g \in G, t \in T_g^a, \tag{4.14}$$

$$w_{g',t+l_g}^a - w_{g,t}^d = 0 \qquad \forall g, g' \in G, t \in T_g^d, \tag{4.15}$$

$$w_{g,t}^a - w_{g,t-1}^a \ge 0 \qquad \forall g \in G, t \in T_g^a, \tag{4.16}$$

$$w_{g,t}^d - w_{g,t-1}^d \ge 0 \qquad \forall g \in G, t \in T_g^d, \tag{4.17}$$

$$w_{g,t}^a \in \{0,1\} \qquad \forall g \in G, t \in T_g^a, \tag{4.18}$$

$$w_{g,t}^d \in \{0,1\} \qquad \forall g \in G, t \in T_g^d. \tag{4.19}$$

$$c_g = \beta * DIP_g + \gamma * HAZ_g + \varepsilon / PRTY_g + \omega / (TIME_g + 1) \tag{4.20}$$

Appendix B: Glossary of Acronyms

AB	Air Base
ACC	Air Combat Command
AE	Aerial Evacuation
AFB	Air Force Base
AFI	Air Force Instructions
ALT	Available to Load Time
AMC	Air Mobility Command
AOR	Area of Responsibility
APCC	Aerial Port Control Center
APOD	Aerial Port of Debarkation
APOE	Aerial Port of Embarkation
AR	Air Reserve
BASH	Bird Air Strike Hours
CAMPS	Consolidated Air Mobility Planning System
CDD	Crew Duty Day
CIA	Central Intelligence Agency
CINC	Commander in Chief
CONUS	Continental United States
CRAF	Civil Reserve Air Fleet
DDO	Deputy Duty Officer
DIPS	Diplomatic Clearance
DLA	Defense Logistics Agency
DO	Duty Officer
DoD	Department of Defense
DLA	Defense Logistics Agency
DTS	Defense Transportation System
FHP	Flying Hour Program
FMOG	Fueling Maximum on Ground

GATES	Global Air Transportation Execution System
GDSS	Global Decision Support System
GUI	Graphical User Interface
HAZMAT	Hazardous Material
HR	Human Remains
ICAO	International Civil Aviation Organization
IP	Integer Program
JCS	Joint Chiefs of Staff
JA/ATT	Joint Airborne/Air Transportability Training
LP	Linear Program
MAC	Military Airlift Command
MOG	Maximum on Ground
MSC	Military Sealift Command
MTMC	Military Traffic Management Command
NATO	North Atlantic Treaty Organization
NOR	Net Operating Result
OCONUS	Outside the Continental United States
OPCON	Operational Control
PAX	Passengers
PMOG	Parking Maximum on Ground
SAAM	Special Assignment Airlift Mission
SAC	Strategic Airlift Command
TACC	Tanker Airlift Control Center
TALCE	Tanker Airlift Control Element
TCC	Transportation Component Command
TDD	Time Definite Delivery
UN	United Nations
US	United States
USTRANSCOM	United States Transportation Command
WMOG	Working Maximum on Ground

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